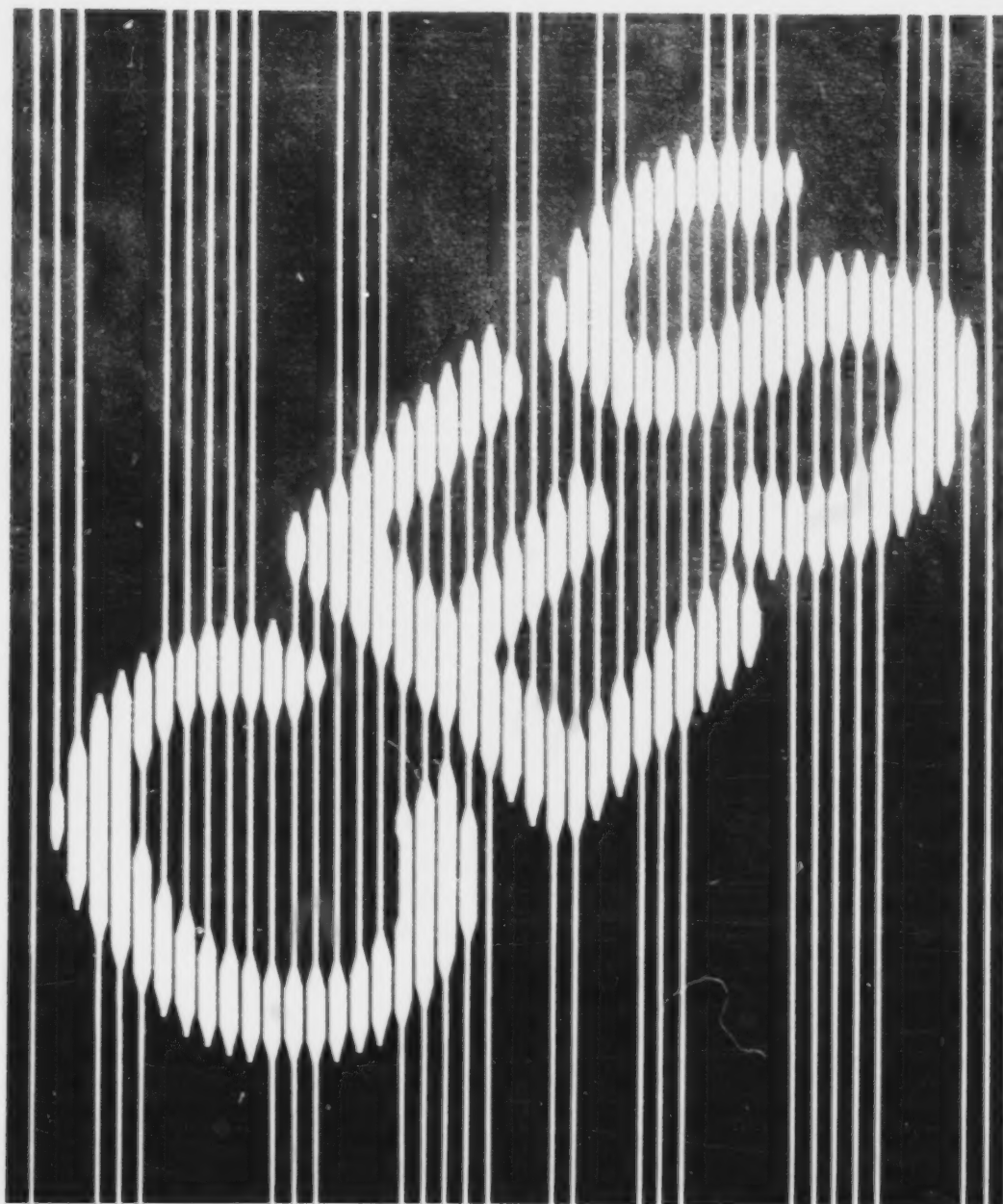


MEASUREMENT OF BURNING RATE OF SUNCOR COKE
IN A CIRCULATING FLUIDIZED BED COMBUSTOR

Contract No. 1ST84-00136



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MICROMEDIA

PREFACE

This is the final report on work performed under a contract with Supply and Services Canada.

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Title: Measurement of Burning Rate of Suncor Coke In A Circulating Fluidized Bed Combustor

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ABSTRACT

The burning rates of Suncor coke particles are measured in a 102 mm dia x 4500 mm tall circulating fluidized bed combustor. Preburned coke particles were ground down to an approximate spherical shape in the size ranges of 14 - 4 mm and were preheated to the bed temperature in an inert atmosphere of nitrogen. The circulating fluidized bed of 135 micron sand was heated by propane to approximately 850°C and operated at 6, and 7 m/s superficial fluidizing gas velocity. The solid recycle rate was fixed at 113 kg/m³s. The sample particles were dropped into the bed through an air lock. Particles were allowed to burn for a 5-20 minute period after which the bed was flushed with nitrogen to quench combustion. The overall burning rate in the fast bed and in the return leg was calculated from the weight loss rate and an estimated attrition rate.

The overall burning rate was lower than that in bubbling beds and it was higher at 7 m/s than at 6 m/s. The burning rate increased with coke diameter. Even though the overall burning rate was low, a tentative calculation suggested that the burning rate inside the fast bed is much higher than that in bubbling beds.

RÉSUMÉ

Les taux de combustion de particules "Suncor coke" ont été mesurés en utilisant un lit fluidisé circulant mesurant 102 mm de diamètre et 450 mm de hauteur. Les particules de coke furent broyées jusqu'à ce qu'elles atteignent une forme quasi-sphérique de grosseur variant entre 14 et 4 mm. Celles-ci furent ensuite pré-chauffées à la température du lit fluidisé à l'intérieur d'une atmosphère inerte d'azote composé de sable (135 microns) et circulant à l'intérieur de la chambre de combustion à des vitesses approximatives de 6 et 7 m/s, fut chauffé au moyen de propane jusqu'à une température approximative de 850°C. Le taux de recyclage des solides était fixé à 113 kg/m²s.

L'échantillon de particules fut introduit au lit fluidisé par une poche d'air (air lock) et alloué de brûler pour une période de vingt minutes après quoi la chambre fut remplie d'azote pour mettre fin à la combustion. Le taux de combustion total à l'intérieur du lit rapide et de la boucle de retour fut calculé en utilisant le taux de perte de poids et en estimant la perte de poids due à l'usure.

Le taux de combustion total était inférieur à celui d'un lit à bulles et plus élevé à la vitesse circulante de 7 m/s qu'à celle de 6 m/s. Le taux de combustion augmentait avec une augmentation du diamètre des particules. Même si le taux total de combustion était bas, un calcul tentative indique que le taux de combustion à l'intérieur du lit rapide est considérablement plus élevé que dans un lit à bulles.

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NOMENCLATURE

C_p	Oxygen molar concentration, kmol/m ³
d_{av}	Average coke diameter, m
d_p	Coke particle diameter, cm
D_g	Gas diffusion coefficient, m ² /s $D_g = 0.000208 (T_g/1173)^{1.75}$
D_T	Bed diameter, m
G	Solid Recycle Rate, kg/m ² s
h	Bed height above the recycle point, m
K	Attrition coefficient
K_0	Reaction rate constant, m/s
M	Molecular weight of carbon
m'	True order of reaction
m	Burning rate, kg/s
n	Apparent order of reaction
P	Oxygen Partial Pressure, atm
R	Gas Constant, J/mol K
R_C	(Apparent) Rate coefficient (kg carbon/m ² s (kPa O ₂) ^{0.5})
R_C', R_k	Effective reaction rate based on unit external surface area, (gC/cm ² s)
Re	Reynolds number
R_g	Gas constant (cal/gmK)
R_s	Intrinsic reaction rate per unit surface area, (gC/cm ² s)
S_A	Internal surface area per unit volume of particle, (cm ² /cm ³)

Sh	Sherwood number
T _g	Bed Temperature, K
T _p	Coke particle temperature, (T _g + 66,000 C _p) °K (Ross et. al - 1981)
U	Superficial velocity, m/s
U _T	Terminal velocity, m/s
U _{mf}	Minimum fluidization velocity, m/s
W _{av}	Average coke particle weight, kg
ΔW	Coke particle weight loss rate due to attrition, kg/s
ε	Void fraction
ρ _p	Particle density (kg/m ³)
ρ _g	Gas density (kg/m ³)

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1.0 INTRODUCTION

Oil sand deposits are one of the largest resources of oil in Canada. At present, only two oil sand plants are in operation: the Suncor plant and the Syncrude plant, both situated in Alberta. The Suncor plant is the smaller of the two and has an output of about 60,000 barrels of oil per day.

A large quantity of by-product coke is produced from the Suncor plant's delayed coker. The coke is unreactive, high in sulphur but also high in calorific value. Presently this coke is burnt in conventional down shot pulverised fuel furnaces to supply steam to the oil sand project. The sulphur emission from this plant is a major air pollutant. Thus, research is being pursued for a suitable alternative to its present utilization.

Exploratory work carried out at the Hans Ahlstrom Laboratory of Finland found that Syncrude coke, which is similarly unreactive, may be burnt efficiently in a circulating fluidized bed, thus setting the stage for full scale application of this technology for the utilization of Suncor coke.

Full scale commercial use of this technology can not depend only on trials in a pilot plant of a specific design because they do not provide enough data for plant optimization. This would require basic combustion data on Suncor coke. For example, the minimum height of the circulating fluid bed combustor depends on the burning rate of the coke. The faster the coke burns, the shorter the furnace may be. Since such data are not available in the

literature, the manufacturer would naturally have to overdesign the furnace.

In view of this, the Combustion and Carbonisation Research Laboratory of CANMET contracted out a study on the measurement of burning rate of Suncor coke to this laboratory.

This work provides a first insight into the burning of individual coke particles in a circulating fluidized bed. It also provides some important data on the overall burning rate of coke over a specified range of experimental conditions. Data over the entire range of particle size and operating conditions will save designers from having to over design their furnace.

1.1 Specific Objective

The specific objective of this phase of the contract is to measure the burning rate of Suncor coke over the velocity range of 6-7 m/s and provide data for the effect of coke size on the burning rate over the size range of 4-14 mm.

1.2 Background

The present research was conceived at a time when no information on the combustion mechanism and/or burning rate of single fuel particles in a circulating fluidized bed was

available in the published literature. The existence of fast fluidized bed was recognized, but its transition to either turbulent or pneumatic transport was poorly understood. Even the existence of turbulent or fast fluidized bed was debated by some workers. The physical structure of the fast fluidized bed and its hydrodynamic structure was far from clear. However, the majority of large commercial circulating fluidized bed units operate in a range of operating conditions with characteristics such as enhanced solid back mixing, high gas-solid slip velocity, etc. It was decided to select a range within which most commercial CFB operate; the term "fast bed" is used to define the condition of the main column under this operating condition.

No study of the burning rate or combustion of single fuel particles in a CFB was reported in published literature. Thus, there was a considerable uncertainty about the best experimental technique. CANMET and TUNS explored a number of techniques adopted by Basu (1977) and La Lauze & Jung (1985) for bubbling beds. At the time of writing, no experimental data on the residence time of large (14-4 mm) coke particles in CFB was available. However, Prof. J.F. Davidson, an eminent fluidization scientist, of the University of Cambridge, predicted that these particles will remain in the main column (fast bed) until they burn down to 1 mm or less. Thus, all particles in this experiment would be expected to burn in the fast bed alone. The overall burning rate measured would be the rate in the fast bed and would, therefore, be fundamental data which is not equipment specific. Ultimately this did not prove to be the case.

2.0 REVIEW OF PREVIOUS WORK

2.1 Burning Rate of Coke

The burning rate of coke is defined as the rate of weight loss due to combustion of a coke particle. The volatile content of coke is much less than that of coal. Thus, the combustion of Suncor coke is largely governed by the burning rate of individual devolatilized coke particles which is in turn controlled by the mass transfer and kinetic rates. The kinetic rate is not influenced by the mode of fluidization; it is the same as in bubbling beds. The available information on kinetic rate is described in the subsequent section. No information is available on mass transfer from a single coarse particle to circulating fluidized beds; the present experiment may provide some useful insight.

2.2 Reaction Kinetics Of Petroleum Coke

To model the combustion of coke in industrial boilers it is necessary to know, amongst other things, the order of reaction and the kinetic reaction rate. Field (1969) plotted data on char particles burning at either 5.1 or 10.1 kPa of oxygen and concluded the reaction order to be unity. Young & Smith (1981) recalculated the same data and showed that the reaction can also be interpreted as half order.

Essenhig (1965) and Laurendeau (1978) noted that the reaction order increases from zero at 1000 K to unity at 2000 K with the possibility of fractional order in between.

2.2.1 Apparent Reaction Rate

Experimental measurements of reaction order are often shrouded by the effect of mass transfer outside the particle as well as through the pores. The true order of reaction, m' , is related to the apparent order, n , (based on the external surface) by the expression (Young & Smith - 1981)

$$n = (m' + 1)/2 \quad (1.1)$$

Their experiments were in the temperature range 1000-1800°K.

From a least square analysis of their experimental data, Young & Smith (1981) found that the apparent order of reaction was 0.5. For fine petroleum coke (18-88 micron) and temperature between 1000 and 2300 K the apparent rate coefficient, which incorporates the effect of intrinsic chemical reactivity of the pore surface, is given by

$$R_C = (7 \pm .6) \exp (-82400 \pm 500/R T_p) [\text{kg carbon} / \text{m}^2 \text{ s (kPa O}_2\text{)}^{-.5}] \quad (1.2)$$

The reactivity is sometimes affected by the catalytic effect of vanadium or other trace metals. However, this catalytic effect is said to decrease at higher temperature (1000 - 1800°K) (Mulcahy & Smith 1969).

2.2.2 Intrinsic Reaction Rate

The apparent reaction rate described above combines pore diffusion, adsorption and surface reaction. For highly porous particles it may be appropriate to use the intrinsic reaction rate R_s . The intrinsic reaction rate which is based on the internal surface is especially relevant for highly porous particles and for very low reaction rates such as occur at low temperatures.

If S_A is the internal surface area per unit volume of the particle, the effective reaction rate R'_C based on unit external surface area is written by Daw & Krishnan (1983) as:

$$R'_C = \frac{S_A d_p}{6} R_s \quad (1.3)$$

Thus, the effective reaction rate is directly proportional to the particle diameter

$$R'_C \propto d_p$$

The real situation is different because, with the progress of combustion, the pore surface per unit particle volume may vary with the degree of burnout.

Daw and Krishnan (1983) measured the kinetic rate for Kentucky no. 9 coal. The coal sample was burnt in a tubular reactor where the sample was placed on quartz wool. A preheated mixture of air and nitrogen was passed through this sample at known temperature and velocity. The surface temperature of the sample was measured by a thermocouple inserted directly on its surface. The burning rate was calculated by the weight loss method. The mass transfer component was measured separately by sublimation of naphthalene in the same reactor.

The measured effective reaction rate (per unit external surface area) was

$$R_k = 0.912 d_p \exp(-11500/RT_p) P^{0.6} [\text{gC/cm}^2\text{s}]$$

(1.5)

valid between $.03 < d_p < 0.7$ cms

The reaction rate correlation of Field (1967) is used to estimate mass transfer from the measured burning rate. The expression is more simple than that of Young & Smith (1981); it was used by Turnbull & Davidson (1984).

$$K_0 = 595 T_p \exp(-149200/R T_p)$$

(1.6)

3.0 T.U.N.S. CFBC FACILITY

3.1 Introduction

The circulating fluidized bed combustor (CFBC) facility at Technical University of Nova Scotia (TUNS) was designed, built, and made operational by the staff of the Centre for Energy Studies with partial funding from the university. The contract was awarded on the basis that the unit could achieve operating temperature. After the receipt of the contract, the unit was modified to overcome some mechanical difficulties. The following section describes the unit and its operating procedure. Figure 1 is a schematic of the unit.

3.2 The Test Rig

The T.U.N.S. CFBC test unit consists of the following:

- 102 mm (4 in.) diameter combustor
- hot cyclones
- solids return leg
- solids recycle system
- preheater.

3.2.1 The Combustor

The combustor is a schedule 40 stainless steel pipe, 102 mm in diameter

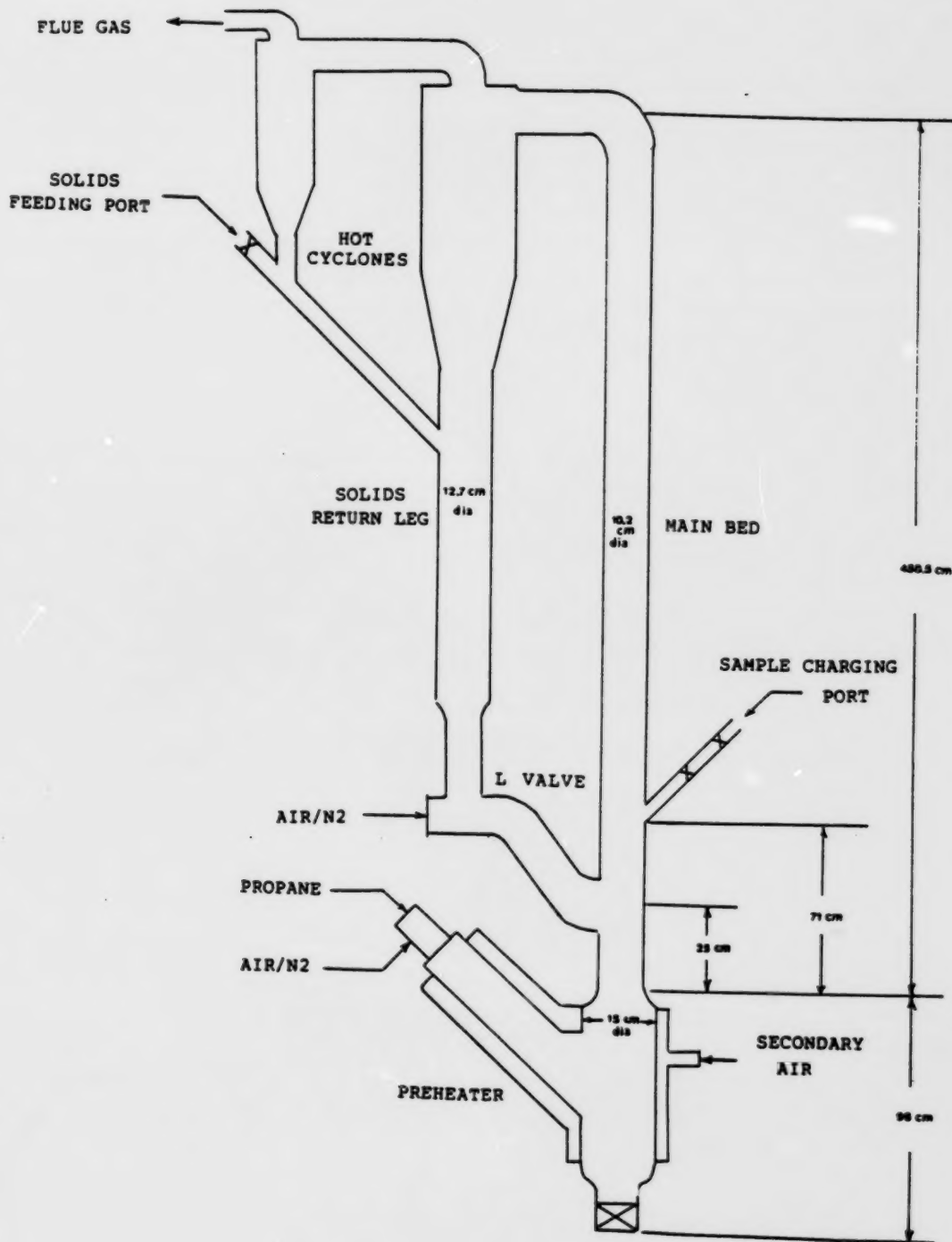


Figure 1. The TUNS CFBC Test Unit

and 4.5 m height. There are pressure, temperature and gas sampling ports at 0.61 m intervals along the height of the combustor. The combustor is insulated with three layers of 25.4 mm ceramic fiber blanket insulation. At the base of the combustor is a solids drain valve. The sample charging port is at about 0.71 m from the base; it operates by a double valve mechanism. Fluidized solids exit the combustor into a series of hot cyclones. The recycled solids re-enter the bed about 0.25 m from the base.

3.2.2 The Hot Cyclones

Solids separation is achieved by two hot cyclones in series. The primary cyclone is above the return leg and is refractory lined. The secondary cyclone has the same inner dimensions as the primary but is unlined. The dip-legs of the primary and secondary cyclones are connected by a 76 mm diameter pipe. The pipe extends beyond the secondary cyclone to a solid feed hopper from which the bed is charged with sand on startup. The cyclones are shown in Figure 2; both are insulated with ceramic fiber.

3.2.3 The Return Leg

The return leg is an insulated 127 mm diameter stainless steel pipe. Its base is connected to the combustor, the fast leg, by a 76 mm diameter L-valve.

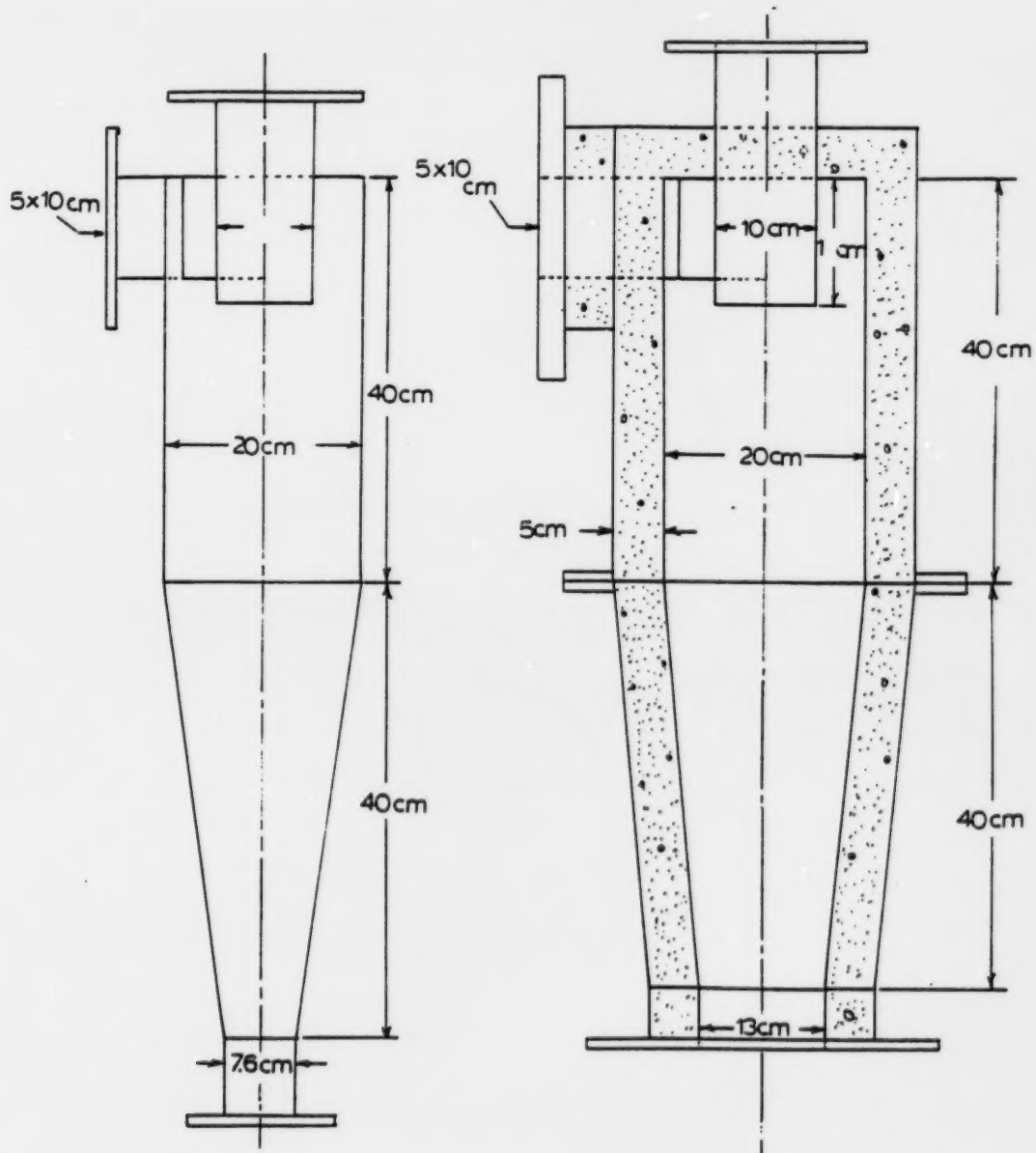


Figure 2. Details of Hot Cyclones

The purpose of the return leg is to return the fluidized solids from the cyclones to the combustor and provide a solid inventory to prevent gas from by-passing the combustor.

3.2.4 The Solids Recycle Systems

The solids recycle system consists of a non-mechanical L-valve (Figure 3). Sand collected in the return leg is "pulsed" into the combustor by a jet of air from a nozzle. The nozzle is a 16 mm stainless steel tube protruding into the valve. The position of the tube is critical since it affects the recycle rate. The valve has two baffles to prevent the trickling of sand by gravity. A continuous stream of air through the L-valve prevents oscillation of oxygen concentration in the bed.

3.2.5 The Preheater

The preheater is a propane burner in a double jacketed stainless steel housing. Primary air is fed into the combustor through the burner. For the contract experiments, the bed temperature is maintained solely by the preheater; details of the preheater are given in Figure 4. The housing is welded onto the combustor and has a gate valve at its base to allow draining of bed material. Secondary air for cooling is passed through the outer jacket of the burner housing and enters the bed through orifices near the entry of the burner.

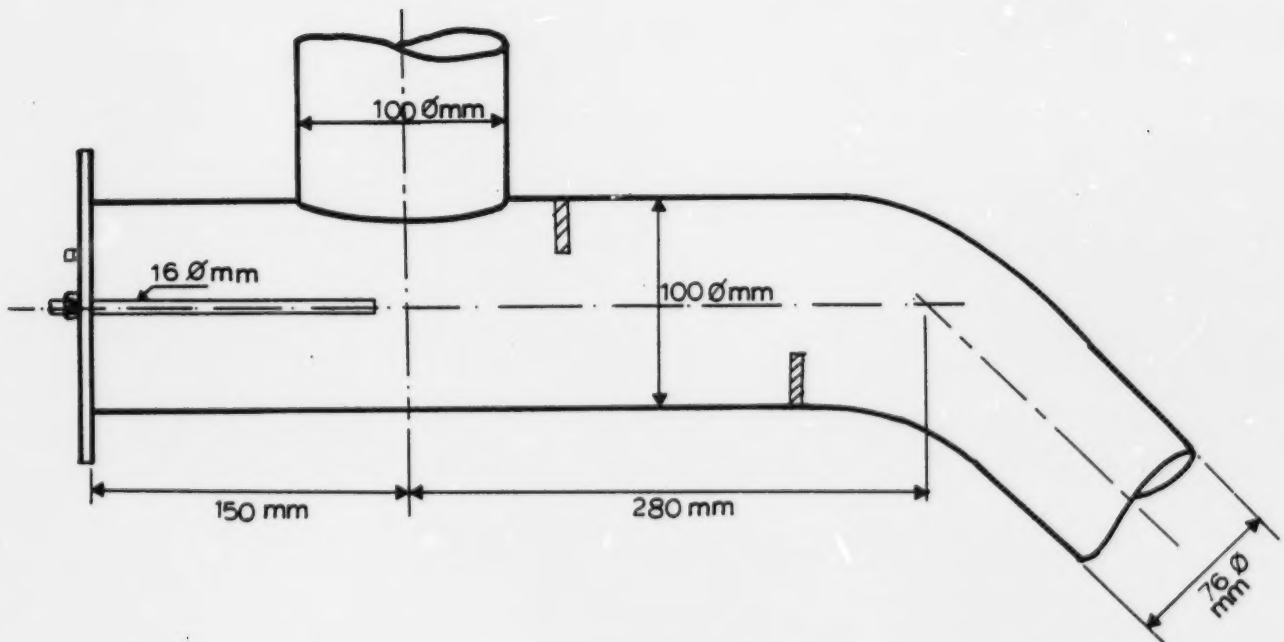


Figure 3. Details of L-Valve

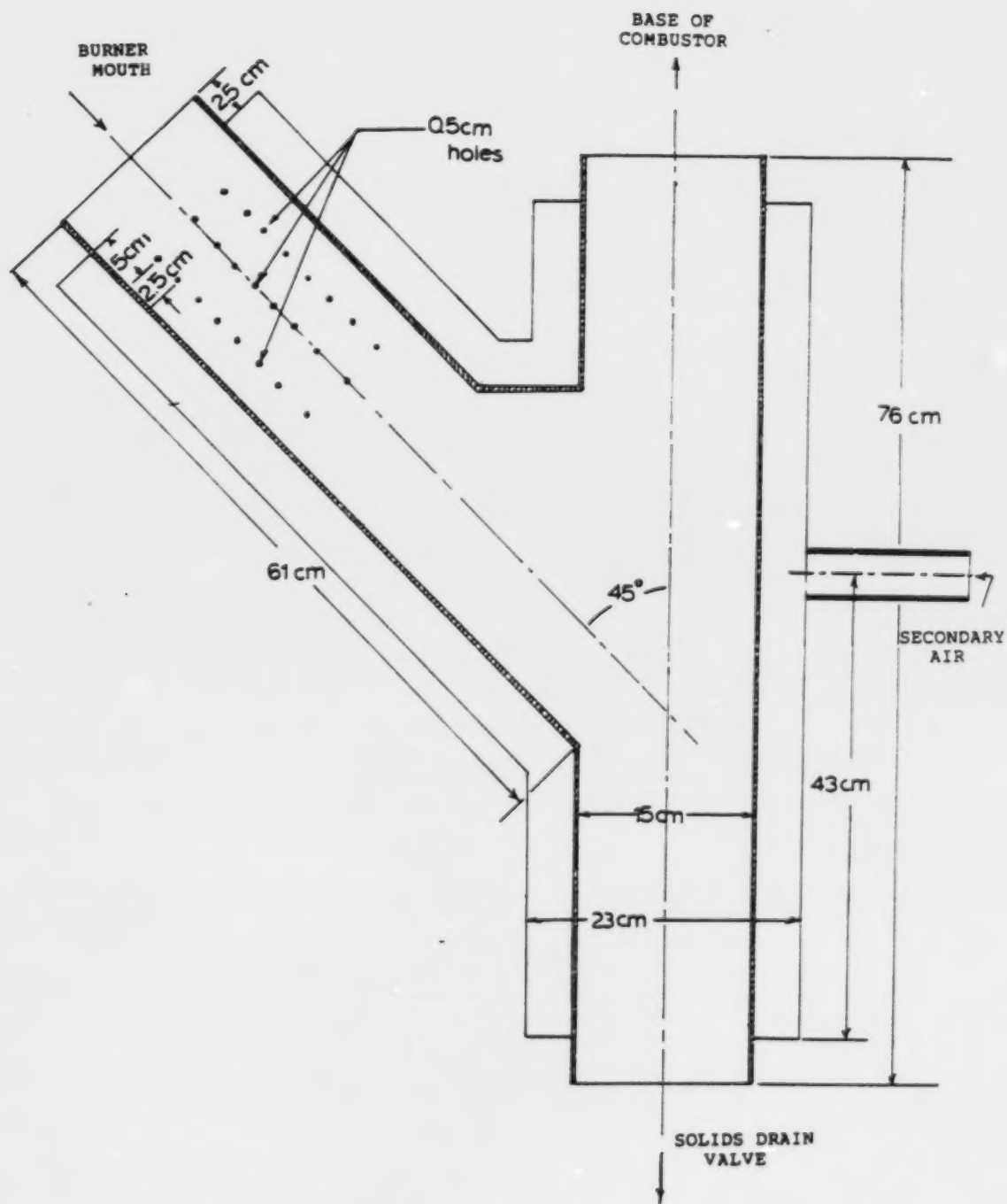


Figure 4. Details of Preheater

3.3 Operating Procedures

3.3.1 Start-Up

The following procedures are performed during start-up:

- a) the return leg is filled with sand
- b) the burner is turned on and the empty bed is allowed to heat up to 600°C.
- c) the solid circulation is begun
- d) the sand inventory in the return leg is replenished
- e) the bed is left to rise to operating temperature; the heat up period is from two to three hours. As the temperature increases, the gas expands resulting in higher fluidization velocity (6-7 m/s) leading up to fast fluidization.

3.3.2 Maintaining Operating Conditions

The bed temperature is maintained by controlling the propane flow rate. Air flow rates are kept constant at the velocity required at the operating temperature. The solid recycle rate is kept constant with a constant air flow rate through the L-valve.

3.3.3 Bed Quenching and Cool Down

The bed can be flooded with nitrogen through the L-valve and the primary

and the secondary air lines to quench combustion. When quenching occurs, the propane and air flow are stopped. Nitrogen can be fed into the L-valve separately to quench combustion in the return leg; Figure 5 shows the piping diagram for the unit. Cooling of the bed is achieved by shutting off the propane burner. The time to cool-down to room temperature is from eight to ten hours. The time may be shortened by continuously passing air through the bed.

3.4 Measured Parameters

The measured parameters include:

- a) oxygen concentration
- b) bed pressure drop
- c) bed temperature
- d) gas flow rates

3.4.1 Oxygen Concentration

The oxygen concentration in the bed is measured at the base of the bed, at the top of the bed and at the return leg. Since the concentration difference was small, the value at the top of the bed was used in all experiments. The sampling line includes a particle filter at the sampling point, a vacuum pump, and a moisture trap. The oxygen concentration is measured with a Beckman model 7003 analyzer which has an error of $\pm 3\%$. The analyzer was calibrated with air before each measurement. The data from the analyzer is displayed on a strip chart recorder.

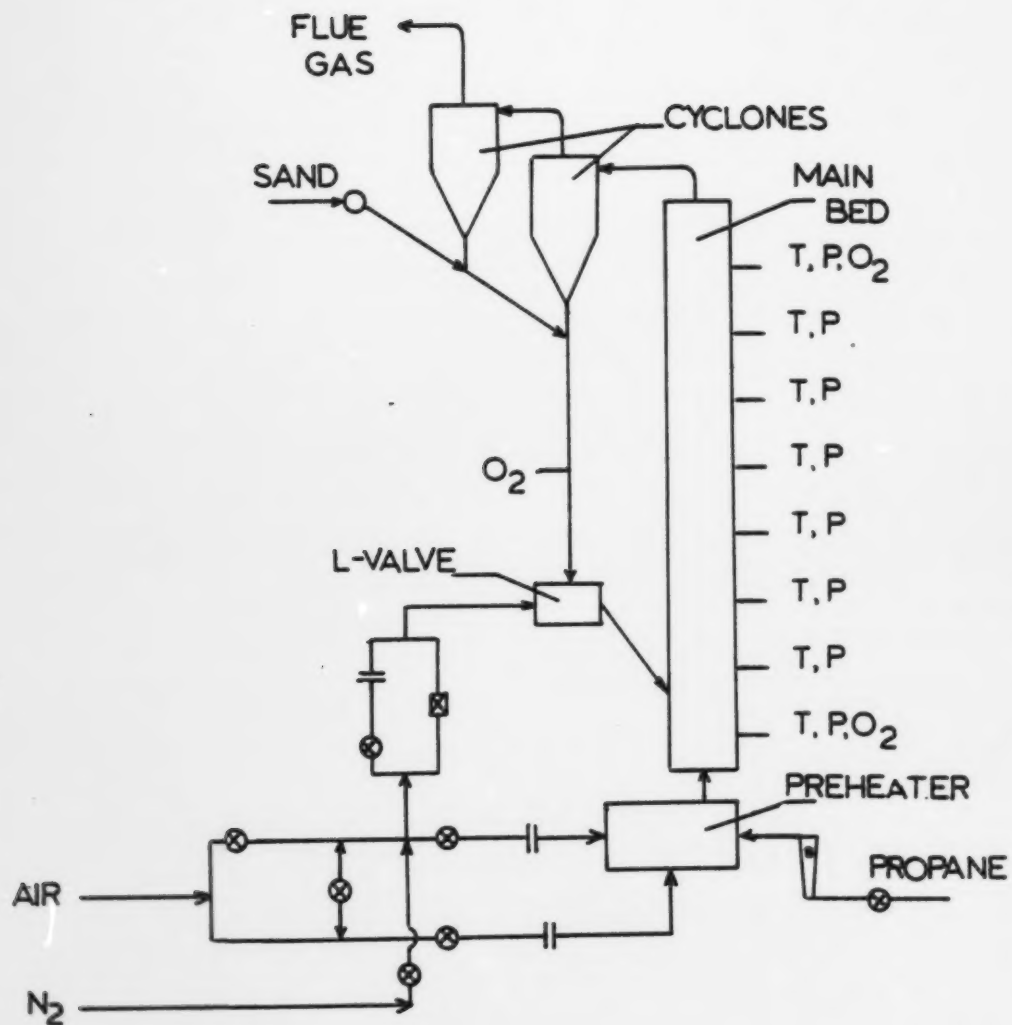


Figure 5. Piping Diagram of the CFBC

3.4.2 Pressure Profile

The pressure is measured every 61 centimeters up the column of the bed. The pressure profile is obtained from a central manometer array; eight measurement points are connected to eight manometers with a common base. The difference in liquid height between any two manometers indicates the pressure drop between the measurement points. A visual observation shows the nature of the solid hold-up in the bed. The error in the pressure drop measurement due to pressure fluctuations is in the range of $\pm 3\%$.

3.4.3 Bed Temperature

The temperature measurements are made with type-K thermocouples. Initially these measurement points were at the same levels as the pressure measurement ports; however, the hostile nature of the bed environment rapidly eroded the thermocouples. These thermocouples were replaced with three thermocouples placed at the base, half-way up, and at the top of the bed. These have an outer stainless steel sheath that is replaced after every 30 hours of operation. The error in temperature measurement is $\pm 1^\circ\text{C}$.

The temperature measured in the return leg was similar to the one in the main bed. When there is no, or very little recycling of solids, a large temperature gradient is observed up the height of the main bed. The temperature gradient disappears suddenly after the recycle rate exceeds a critical value. This may be associated with the onset of fast fluidization because a large

scale backmixing of solids, which is characteristic of fast fluidization helps reduce the temperature gradient. In this situation, the temperature measured in the return leg was similar to that in the main bed.

3.4.4 Flow Measurements

Four gas lines are connected to the bed; three are for primary, secondary and refeed air and one is for propane. Each of the air lines is fitted with standard orifices; the propane flow is monitored with a rotameter. The air is supplied by the University's compressor. The flow rate is calculated by orifice equations. The superficial velocity varies by $\pm 2\%$ due to bed temperature fluctuations and pressure surges in the air line.

4.0 EXPERIMENTAL PROCEDURE AND PROGRAM

4.1.0 Experimental Procedure

The purpose of this project is to study the instantaneous burning rate of coke particles; this parameter governs the performance of a CFB boiler. On entry into the bed, a fuel particle is rapidly heated and devolatilised. The period of preheating, devolatilization and volatile combustion is a small fraction of the time taken by the residual carbon to complete its combustion. Thus, the vast majority of fuel particles in the bed are in the phase of combustion of devolatilised coke. In this experiment, fuel particles were devolatilized and partially burnt before dropping into the bed. In subsequent tests, the same fuel particle was quenched, cooled and burnt again in the bed. La Nauze & Jung (1982) also used this technique to simulate the progressive burning of the fuel particle. In a CFB boiler, a fuel particle moves alternately between the hot zone (combustor) and a cold zone (fluid bed heat exchanger under the cyclone). Thus, the present procedure of alternate heating and cooling of the coke particle is similar to the real situation.

Daw & Krishnan (1983) expressed the possibility that the amount of internal surfaces may depend on the rate of preheating of the particle. The internal surface area will dominate the combustion when oxygen reaches all internal pores. It is not known whether this is the case in a CFB. An exploratory test was carried out with one particle preburnt in a CFB and another preburnt in a furnace. Burning rates of these two otherwise identical particles were found to be similar.

The experimental procedures include:

- sample preparation
- burning of samples
- quenching and retrieval of samples

4.1.1 Sample Preparation

In preparing samples, the coke is preburned in a furnace at 750°C for 15 minutes. This allows the coke to undergo shattering before being subjected to the circulating bed environment. Preburned particles are then hand-ground to an approximate spherical shape and measured according to contract specifications. Initially, particles were shattered in a CFB, but tests showed that there was no difference in the burning rate whether the particle shattered in a furnace or in a CFB.

4.1.2 Burning of Samples

Once the bed is at operating temperature and the required velocity is set and stabilized, a charge of prepared samples is heated by hot nitrogen gas and dropped into the bed. The particles are allowed to burn for a predetermined time and then the bed is quenched with nitrogen and the particles retrieved.

4.1.3 Sample Quenching and Retrieval

The quenching and retrieval process is as follows:

- 1) all air and propane into the bed is stopped
- 2) the bed is flooded with nitrogen
- 3) bottom valve is opened to drain solids
- 4) coke particles are retrieved with a stainless mesh screen
- 5) nitrogen from a blower gun is used to completely quench combustion when the particles are sitting on the screen.

The particles are collected and reweighed on an analytical balance. The measurement is accurate to $\pm 5 \times 10^{-4}$ gm. The time measurement is accurate to ± 10 seconds.

4.2 Experimental Program

The experimental program was divided into the following tasks:

1. Analysis of coke
 - 1.1 Proximate and Ultimate
 - 1.2 Porosity
 - 1.3 Density

2. Preliminary tests

2.1 Pressure profile

2.2 Temperature profile

2.3 Solid recycle

2.3.1 Pulsed feed

2.3.2 L valve

2.4 Attrition rate

2.5 Shattering tests

2.6 Movement of coke in the CFBC

3. Contractual burning rate tests

3.1 Trials on 7 m/s

3.2 Trials on 6 m/s

4.2.1. Analysis Of Coke

4.2.1.1 Proximate & Ultimate

The Suncor coke, supplied by the Alberta Research Council, Edmonton, was sent to the Nova Scotia Research Foundation. The ultimate and proximate analyses of the sample are given in Appendix I. Since the entire experiment was carried out with samples from the same drum, only one sample was prepared by the random sampling technique. As expected, the volatile matter of the coke was low.

4.2.1.2. Porosity

The TUNS Coal Research Laboratory measured the porosity of the coke samples. Micro and macro pores were measured. The BET surface area before combustion in the CFB was in the range of 3.1 - 3.4 sq. m/gm while that after combustion was about 6.19 sq. m/gm. This may suggest some pore combustion but results are too few for a definite conclusion. Distribution of the pore areas are given in Appendix II.

4.2.1.3. Density

The density of coke was measured by the water displacement method. A $\pm 5\%$ variation from the mean value of 1176 kg/m^3 was noticed between samples. Even though the particle diameter was calculated on its measured weight, diameters of random samples were measured on three planes with the help of a micrometer to check the density. The change in density with burnoff was within the above $\pm 5\%$ experimental error.

4.2.2. Preliminary Tests

4.2.2.1. Pressure Profile

The most reliable indication of the existence of a fast fluidization is the variation of voidage along the height of the bed. In a bubbling or turbulent bed, there is a sharp difference in bed density (1- voidage) between

the top and the bottom of the bed. Slugging will be indicated by fluctuating pressure drop across any section of the bed. The transport zone is characterized by uniform high voidage along the bed height.

Subba Rao and Basu (1985) derived an expression for the voidage distribution along the height of the fast bed by neglecting wall friction and particle acceleration.

$$(1-\epsilon) = \frac{1}{2} \left[\frac{G}{\rho_p u} \right]^{7/6} \left[\frac{1.89 D_T \rho_p}{h \rho_g} \right]^{1/2} \quad (2.1)$$

$$h > 0.25 \text{ m}$$

The expression indicates a steady drop in bed density with bed height. A typical voidage profile (Figure 6) measured along the bed shows a steady decline as in Eqn. 2.1 and confirms the existence of a fast bed.

4.2.2.2. Temperature Profile

A sharp change in temperature profile was noticed when the bed changed from bubbling to fast or from transport to fast regimes. In either case, the temperature gradient of 200 - 300°C over the height of 4 meters reduced to 10 - 20°C when fast fluidization was reached. A typical bed temperature profile is shown in Figure 7.

No investigation was made of the hydrodynamics of the bed. The rationale for using the term "fast bed" is:

- (a) In a captive state of fluidization (bubbling or turbulent) the voidage is very low (.6-.85) within the bed and there is a sharp change in voidage to greater than .995 above the bed surface. The voidage profile shown in figure 6 does not show such a sudden change in voidage.
- (b) Had the bed been in pneumatic transport there would be negligible solid backmixing and, hence, there would be a large temperature gradient along the height of the bed. In the present experiment this temperature gradient was absent.

As explained in Section 1.2, there is uncertainty about the term "fast bed"; the exact nature of fast beds is unclear. Furthermore, it is hard to predict the exact transition from captive state of fluidization to the fast regime or from the fast regime to pneumatic transport. Thus, it was decided to operate in the velocity range of 6-7 m/s in a bed of 135 micron sand at a solid recycle rate of around 113 kg/m²s, because most of industrial CFB boilers operate in this regime.

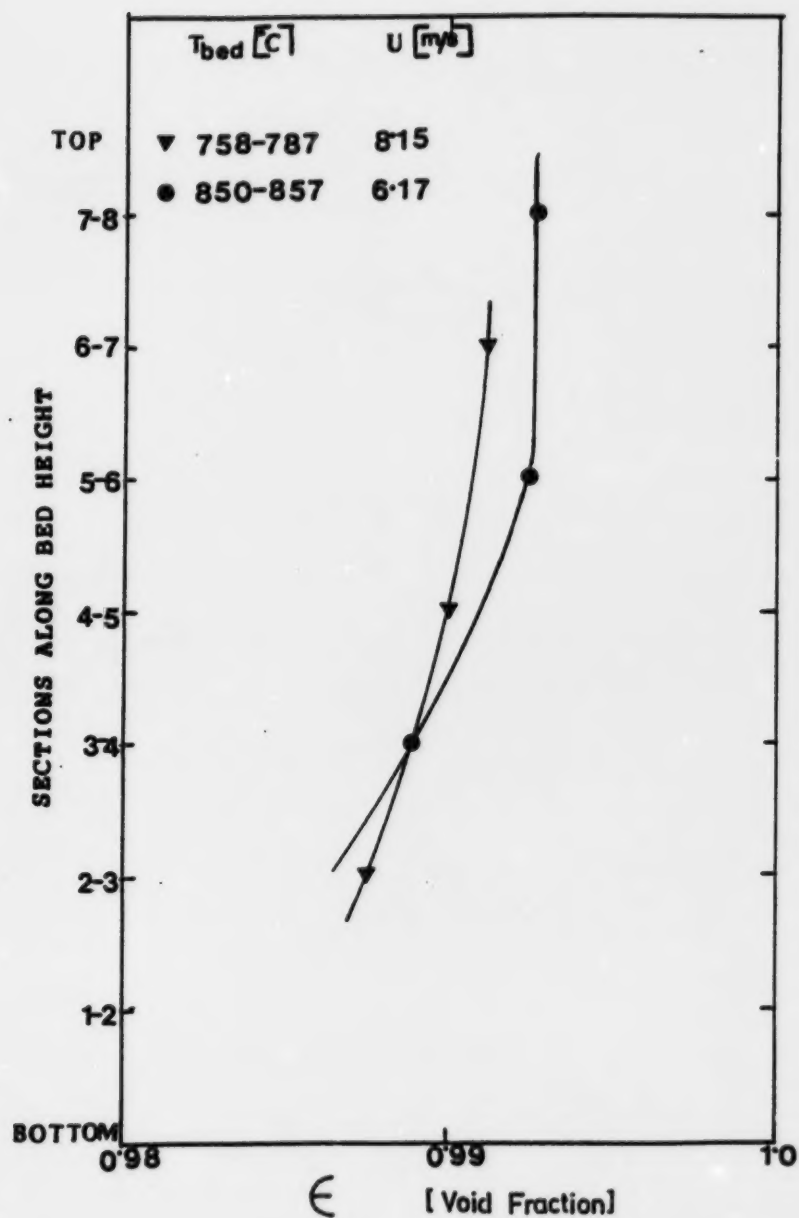


Figure 6. Bed Voidage Profile

4.2.2.3. Solid Recycle

Three techniques were attempted in recycling solids at regulated rates.

- a) Auxilliary fluidized bed
- b) Pulsed feeder
- c) L-valve

In the absence of published design data, an ad hoc design of the auxiliary fluidized bed was adopted but it failed to recycle the solids properly.

A pulsed feeder was built following Kwauk's design (Kwauk - 1984). It operated successfully and the recycle rate could be varied with the pulse frequency.

In certain experiments, an unusual surge (Figure 8) in oxygen concentration was observed with this pulsed recycle device. The frequency of the surge was several times higher than that of the pulser and it did not seem to have any connection with the switching (on or off) of the air compressor. When a continuous L-valve solid recycle feeder was used, no surge in oxygen concentration was observed.

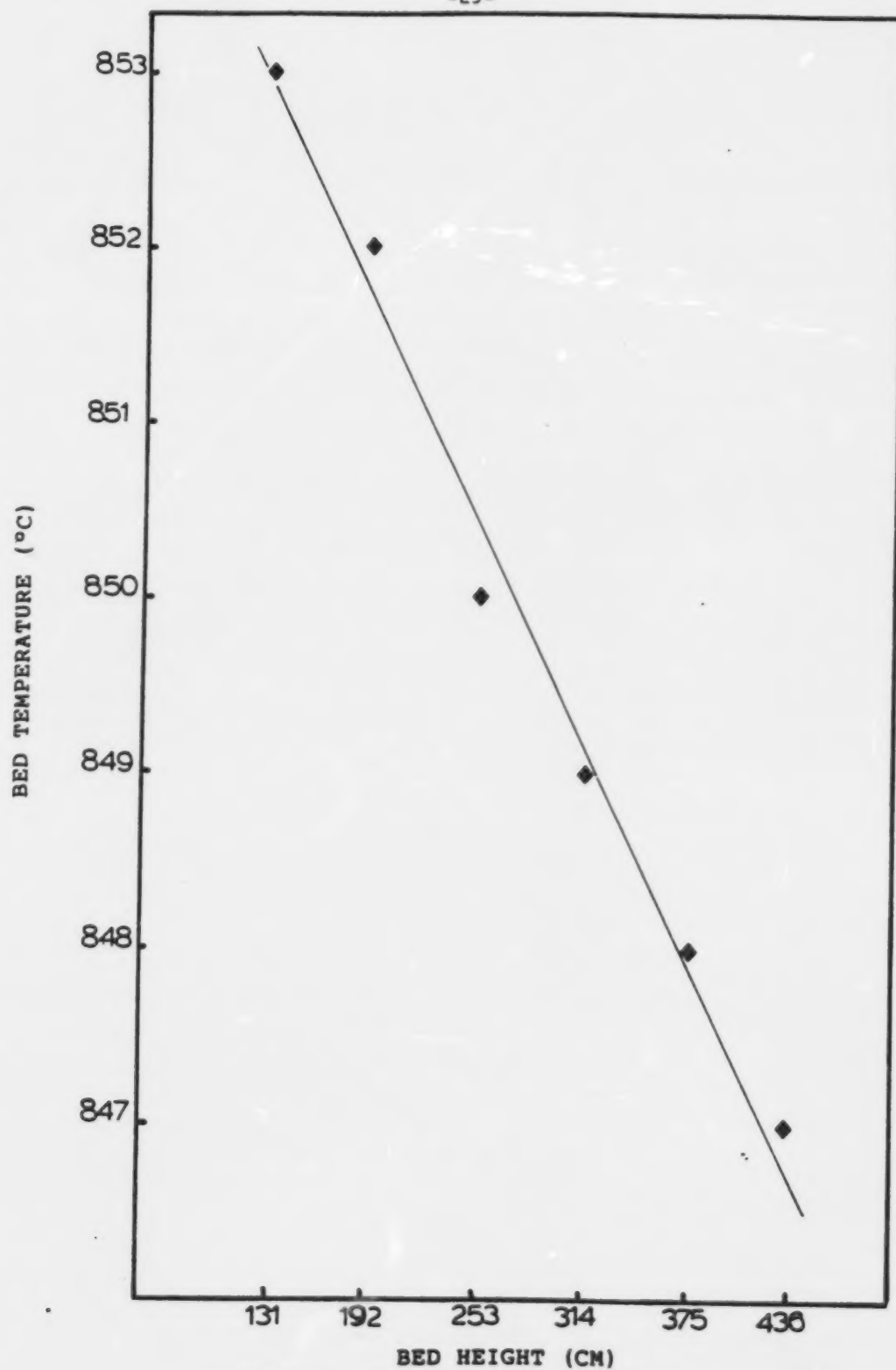


Figure 7. Bed Temperature Profile

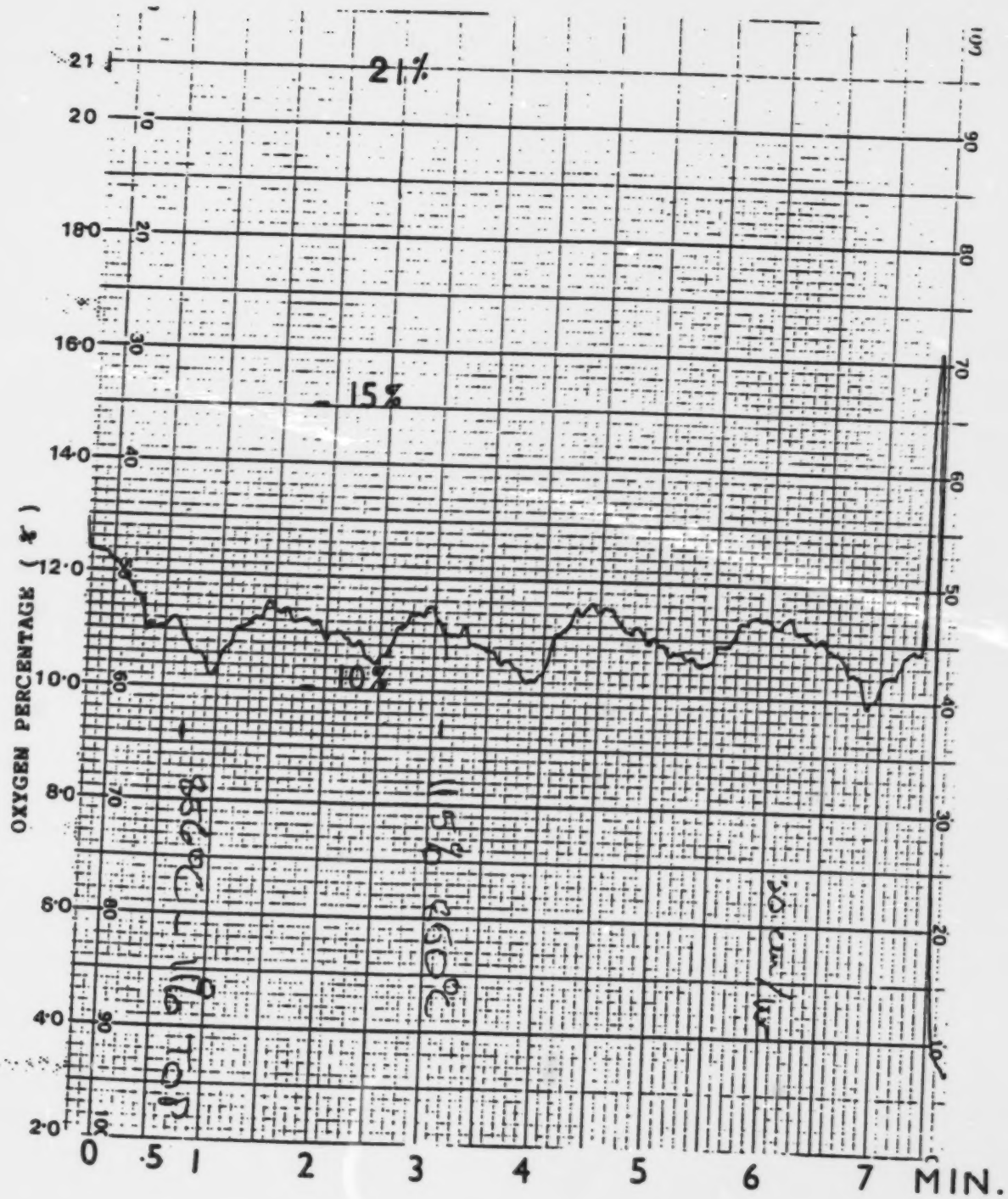


Figure 8. Surges In Oxygen Concentration During A Run With Pulsed Air Through the L-Valve

The L-valve was used in most burning rate tests. These non mechanical valves were calibrated in both hot and cold conditions.

The main bed was not fluidized when calibrating at room temperature. The solids were recycled and collected under the main bed for a specified period of time. The recycle rate was calculated by dividing the weight of solids collected by the collection time.

In the hot bed measurement, a lump of coal fines was dropped on the surface of the solid column in the return leg. These particles burned brightly in the column and descended with the return solids. The time taken for these brightly burning carbon particles to travel from the top of the solid column to the exit of the return leg was measured by observing their flow past a window located at the exit. The bed was slumped and the solid content of the return leg drained and measured. The recycle rate was obtained by dividing the weight by the travel time of coal fines and by the cross-sectional area of the return leg. Since, in the present contract, the solid recycle rate is not a major item of study, it was measured only for a limited number of operating conditions.

4.2.2.4. Attrition Rate

Attrition rate is a major source of weight loss of carbon particles burning in fluidized beds. Arena et al. (1983) measured attrition rates in a

bubbling fluidized bed. The experiments did not show any dominant effect of temperature on the attrition coefficient; thus, we have used data from cold beds to describe hot beds. While the combustion assisted attrition is recognized, it has not been taken into account as a first approximation in this work.

No data on the attrition rate of coke in a circulating fluidized bed was available in the literature. Batches of coke were attrited in a cold circulating fluidized bed over a given period of time. The attrition coefficient was measured from the weight loss using the equation of Arena et al. (1983).

$$K = \frac{\Delta W_{\text{dav}}}{(U - U_{\text{mf}}) W_{\text{av}}} \quad (2.4)$$

The average value of the measured attrition rate coefficient was 2.29×10^{-8} . In certain cases parts of the coke particle chip off due to mechanical shock. This results in a weight loss several times larger than that for normal combustion. Thus, chipping was easily identified.

4.2.2.5. Shattering Tests

Coke particles shatter when they are first introduced into the circulating fluidized bed; larger particles were found to shatter much more than smaller ones. Detailed study of shattering is beyond the scope of this work. However, it was noted that shattered particles were usually in the range of 1-3 mm and were difficult to retrieve. Table (I) gives the percentage of

shatter for different sized particles from two tests.

TABLE I: SHATTER FOR DIFFERENT SIZED PARTICLES
(A Typical Result)

Velocity m/s	Initial weights (g)	Approximate Diameter (mm)	Percentage of Total Particles Shattered
7.1	1.6850	14	50
	1.064	12	25
	0.616	10	50
	.3150	8	25
	.133	6	0
	.0395	4	0
6.2	1.6850	14	50
	1.093	12	100
	.694	10	100
	.335	8	0
	.145	6	0

4.2.2.6. Movement of Coke in the Circulating Fluidized Bed

Earlier, it was thought (Davidson - 1984) that large (15-5 mm) coke particles will not travel to the recycle leg; large particles stay in the main bed until they burn down to a sufficiently small size to be swept out of the bed and returned via the cyclone.

In the absence of any reported data on this concept, experiments were carried out to check if large particles would move to the return leg. A number of coke particles in the size range 14-4 mm were dropped in the CFBC and the solids from the main bed and return leg were drained after 20 minutes.

The results given in Table II suggest that the large (14-12 mm) particles were swept to the return leg though their calculated terminal velocity is much higher than the fluidization velocity. There is some uncertainty about the terminal velocity of large particles in the present situation where turbulence and the presence of other fine particles may affect the drag coefficient. In the calculation, the drag coefficient was estimated as $18.6/Re^{0.6}$ because it resulted in a better agreement of predicted mass transfer with the measured values for high velocity beds (Basu - Subba Rao - 1985).

TABLE II: COLLECTION OF PARTICLES IN MAIN BED VS RETURN LEG

Velocity 7 m/s; Temperature 854°C

Particles Fed to Main Bed		Particles Collected Under		Lost Through Shattering	U _T m/s
Initial Weights (gm)	No.	Main Bed	Return Leg		
.0395	5	1	4		22
.133	4	1	3		35
.315	4	1	2	1	49
.616	4	1	1	2	63
1.064	4	1	1	2	78
1.685	4	2	2		93

The data confirms the movement of both large and small particles between the main bed and the return leg. At present, no reliable information on the residence time of coarse particles in a fast fluidized bed of fine sand is available. One could estimate the residence time in the return leg by

assuming the solids to be in plug flow; but, the residence time in the fast bed during a particular trip is not known.

4.2.3 Burning Rate Tests

The contract specifies the work to be carried out generally in accordance with the proposal amended in May 1985 which presents the following test matrix.

TABLE III: TEST MATRIX
BURNING RATE OF SUNCOR COKE

Fluidization Velocity (m/s)	6	7
Size of Coke, (mm)	Test No	
14	1.1	2.1
12	1.2	2.2
10	1.3	2.3
8	1.4	2.4
6	1.5	2.5
4	1.6	2.6

Fixed Parameters

Bed temperature - $850 \pm 25^{\circ}\text{C}$

Bed material - sand (approximate mean diameter 100 micron)

Solid recycle rate - $100 \text{ kg/m}^2\text{s}$ approximately

Oxygen concentration - 10% by volume approximately

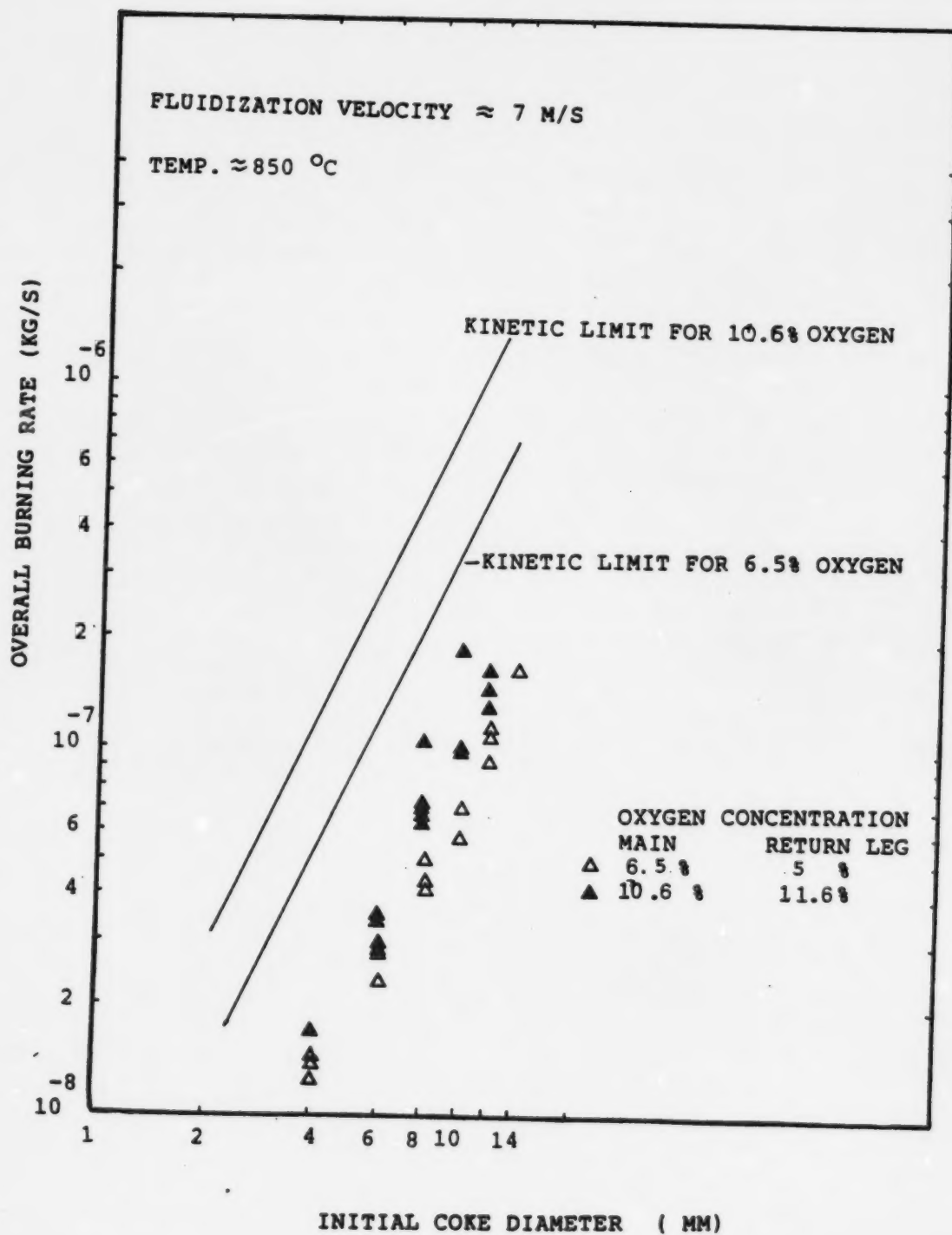


Figure 9. Overall Burning Rate of Suncor Coke At 7 m/s and Recycle Rate at 113 kg/m²s vs. Initial Coke Diameter

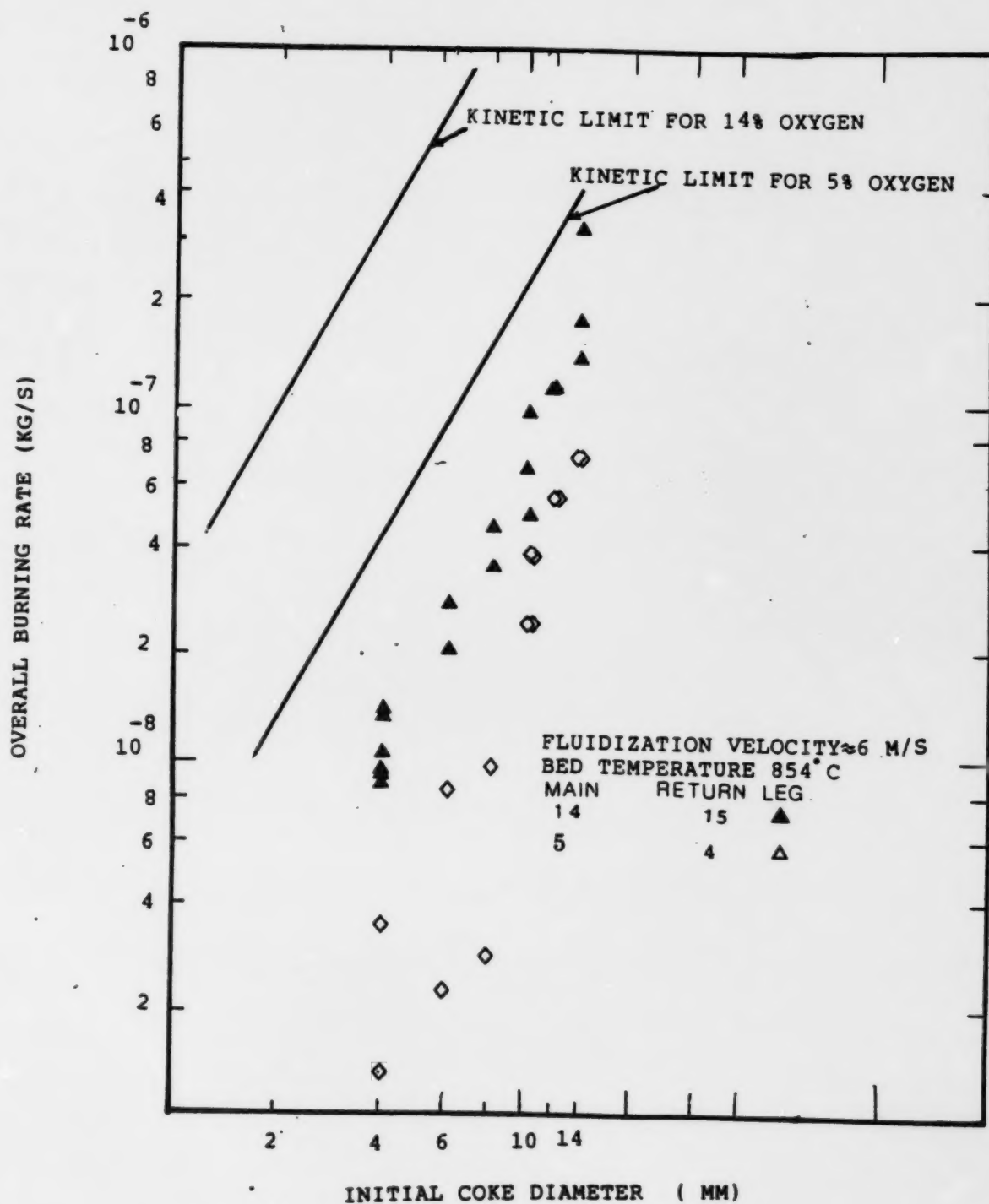


Figure 10. Overall Burning Rate of Suncor Coke At 6 m/s and Recycle Rate At 113 kg/m^2 vs. Initial Coke Diameter

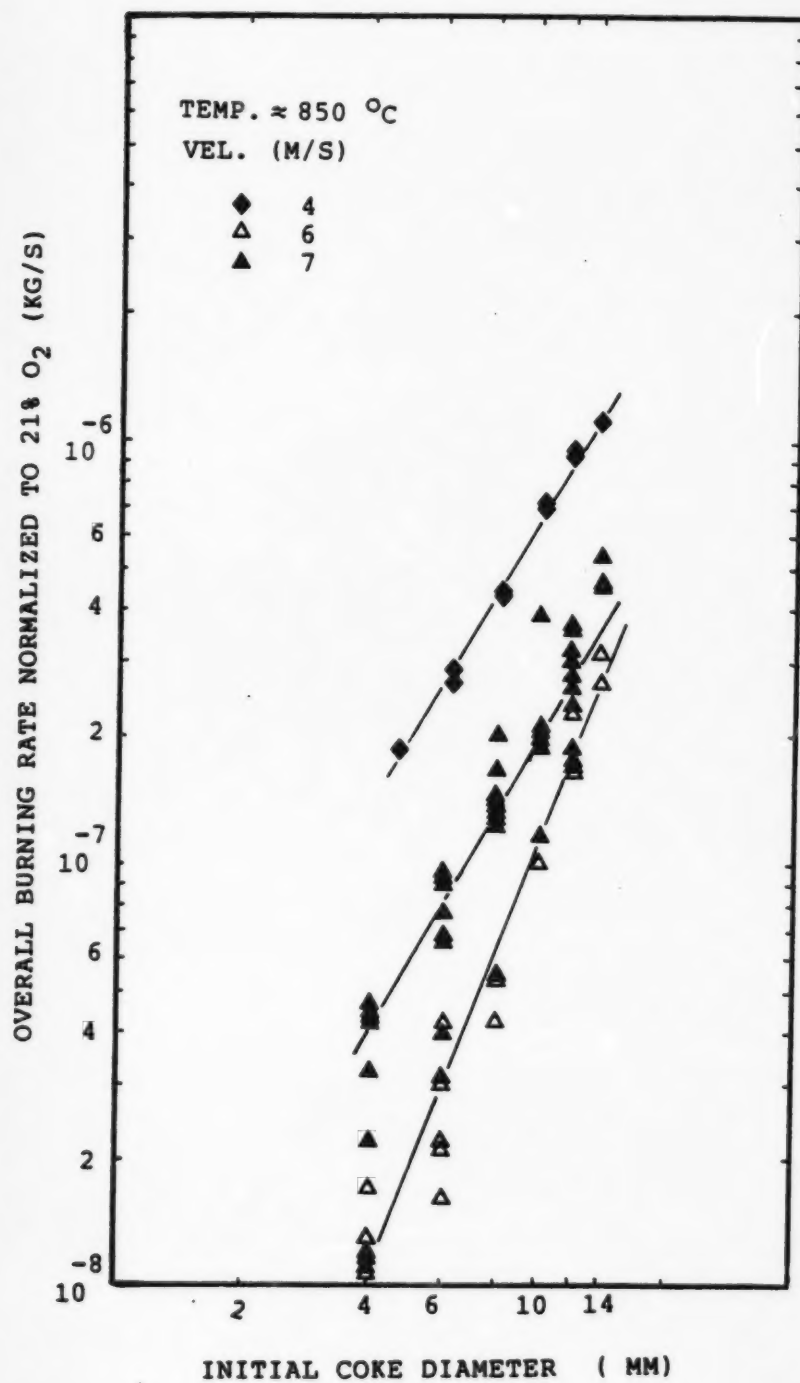


Figure 11. Overall Burning Rate of Suncor Coke At 4, 6 and 7 m/s Normalized To 21% O_2 and Recycle Rate At $113 \text{ kg/m}^2\text{s}$ vs. Initial Coke Diameter

The velocity and coke size cannot be fixed at particular values. The coke is hand ground and burns down to differing sizes; and, the actual velocity is affected by the fluctuations in the bed temperature. Experimental conditions, however, are generally within $\pm 2-4\%$ of the values given above. The oxygen concentration depended on the velocity and the heat loss from the system. Data are provided for oxygen concentration in the range 5% - 15%.

Each of the tests was repeated; unlike graphite, coke is not truly homogeneous. In some of the experiments, fine hair cracks around edges lead to chipping resulting in a high weight loss rate. Furthermore, since the solids are supposed to be in back mixing in a fast bed (Van Swaaij - 1978), the coke particles have a wide distribution of residence times in the bed. When the particle is swept over to the return leg, it moves as in a moving bed where the burning rate is much smaller than that in the fast bed because of poor solid mixing. Therefore, even coke particles of the same size may have different overall burning rates depending on the residence time in the fast bed.

Our experimental observation contradicted Davidson's (1984) observation in that coarse coke particles move freely between the main column and return leg. Thus, the measured burning rate was an average burning rate. It is, however, possible to determine the burning rate inside the fast bed by measuring the residence time of the fuel particles in individual columns. Therefore, it was proposed that on another phase or extension of the present contract the residence time will be measured by radioactive tracer and these data will be used to interpret the data of the present phase of the work.

5.0 Discussion of the Results

Results of tests on Suncor coke at 6 m/s and 7 m/s are given in Tables 1.1 to 2.6. Additional results at 4 m/s and 6.8 m/s and on Syncrude coke are given in the Appendices. Full interpretation of data must await more reliable information on the residence time of coke in the fast bed. In the absence of such information only the overall burning rate can be calculated. The Sherwood number is calculated from the overall burning rate using the expression given by Turnbull & Davidson (1984):

$$m = \frac{M \pi d_{av}^2 C_p}{\frac{1}{K_o} + \frac{d_{av}}{Sh D_g}} \quad (4.1)$$

where M is the molecular weight of carbon: 12.

The overall burning rate is found by subtracting the attrition rate (using rate and coefficient data from Eqn. 2.4). Since the experiments were carried out at different oxygen concentrations, all were brought to a common base using the relation:

$$\text{Normalized Burning Rate} = \text{Observed Rate} \times \frac{\text{Oxygen concentration in fresh air}}{\text{Oxygen concentration in the experiment}} \quad (4.2)$$

The normalized burning rate enables comparison of burning rates measured at different oxygen concentrations. This is an approximate value because the

Kinetic component of the burning rate varies as the half power of the oxygen concentration instead of unity as for the mass transfer component. The tables of burning rate provide relevant data for each experiment.

The following observations are made:

1. There is good mixing of gas between the fast bed and the return leg. The gas (air or nitrogen), used for recycling the solids from the return leg to the main bed, flows into the fast bed with the solids. This is established from the fact that the addition of nitrogen in the return leg causes a drop in oxygen concentration measured at the top of the fast bed.

Oxygen concentration measured in the return leg of the nitrogen pulsed bed was about 4-5%; for the air pulsed bed, it was about 9-10% when the oxygen concentration in the main bed was about 12%. This suggests an induction of gas from the cyclone to the return leg.

2. A low gas-solid relative velocity in the return leg is responsible for poor mass transfer or low Sherwood Number in this leg; the Sherwood number is much less than 2 which is the value for an isolated sphere in a stagnant medium. The occurrence of low Sherwood Numbers in a low Reynolds Number flow through a fixed bed is also observed by other workers (data of Resnik & White and Kettering as discussed by Kunii - 1977).

3. Since coke particles reside longer in the return leg than in the fast bed, the overall burning rate and the mass transfer rate are very low. The significance of this observation is that the overall burning rate can be improved by reducing solid hold up in the return leg, by increasing the solid recycle rate, or by increasing the height of the bed.

The burning rate is plotted against initial particle diameter in Figures 9-11. These show burning rate increasing with coke particle diameter. The burning rate is lowest for 6 m/s. Burning rates at 7 m/s are consistently higher than those at 6 m/s because of a higher slip velocity. The shorter stay in the fast bed at higher velocity will tend to reduce the burning rate, but the higher mass transfer at higher velocity seems to dominate. The highest burning rates are reported for 4 m/s (Figure 11). The smaller scatter of data, higher voidage (.87) and much higher burning rate suggest that this bed was in a turbulent regime which is known to have a higher burning rate (Basu - 1984).

The scatter of data is wider than that observed in bubbling beds (Basu - 1977, LaNauze - 1985). This may be due to the fact that the residence time of a particle in the fast bed is not a unique value; it varies around a mean which depends upon the operating condition. Since there is a large difference in burning rates between the fast bed and the return leg, the combined burning rate will also depend on how long the particular coke particle spent in each leg.

The average burning rate referred to at 21% oxygen is seen to be much below that reported for bubbling fluidized beds for all coke diameters. For example, the rate of burning of a 10 mm coke particle in a bubbling bed (.51 m/s) at 21% oxygen is in the range of $(10 - 11) \times 10^{-7}$ kg/s (LaNauze & Jung-1985) whereas, in a circulating fluidized bed, we observed it to be only $(1.8 - 2.2) \times 10^{-7}$ kg/s at 7 m/s.

Though some segregation may be expected in the return leg, we assume that solids are in plug flow in both return leg and fast bed. The mean residence time in the fast bed is a fraction $W_F/(W_F+W_R)$ of the total time (W_F and W_R are the solid hold up in the fast bed and return leg respectively). Taking typical values of W_F and W_R as 0.825 and 16.78 kg, the residence time in the fast bed is 56 sec. Hence, (neglecting combustion in the return leg) the burning rate in the fast bed is 33.2×10^{-7} kg/s. This rate is much higher than the burning rate in a bubbling bed. The assumptions, however, are limiting. A better interpretation of the data awaits a better estimate on measurement of the residence time in the fast bed.

6.0 CONCLUSIONS

- i) Suncor coke particles shatter when they are first dropped in the hot CFBC. Thereafter, the shattering decreases with burnoff.
- ii) The overall burning rate in a CFBC is lower than that in bubbling beds.
- iii) The overall burning rate increases with particle diameter, but no exact relationship between the coke diameters and burning rates can be established at this stage because the mode of combustion in the return leg and the fast bed may be different. Furthermore, the residence times of the coke particles in individual sections are not known yet.
- iv) Overall burning rates at 7 m/s were consistently higher than those at 6 m/s which suggests an effect of mass transfer or residence time.
- v) Higher burning rates are observed at higher oxygen concentrations.
- vi) Some increase in the porosity (at Angstrom level) is observed after combustion. Further data on porosity measurements are required for a more definite conclusion on pore combustion.
- vii) Coarse (14-4mm) coke particles are entrained from the fast bed even at velocities (6-7 m/s) much below their free fall or terminal velocity.

7.0 SCOPE OF FURTHER WORK

The present work is the first set of data on the burning rate of carbonaceous materials in circulating fluidized beds to be reported anywhere. Thus, these results cannot be compared with others. Therefore, it is important to:

- a) Carry out the experiment over a much wider range of experimental conditions.
- b) Study the residence time of coke in fast beds.
- c) Study the shattering behaviour and the kinetic rate of the delayed coke. The available kinetic rate expressions of petroleum coke may not be appropriate for this coke.
- d) Study the combustion rate of a finer fluid coke such as Syncrude coke. Fluid coke is likely to be more extensively used in future oilsand plants. Furthermore, the finer coke particles have a greater influence on the combustion efficiency of the CFB boiler.

TABLE 1.1 Burning Data of Suncor Coke for 14 mm Particles at 6 m/s

DIAMETER: 14.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
6.17	854	113	.14	0.15	1.6850	1.3025	3.1875	0.1564	3.03	2.2	4.546
			.14	0.15		1.451	1.95	0.1616	1.79	1.2	2.683
			.05	0.04		1.5729	0.9342	0.1832	0.75	1.8	3.154
6.15	858	113	.14	0.15	1.6895	1.506	1.5291	0.1628	1.36	0.9	2.049

TABLE 1.2 Burning Data of Suncor Coke for 12 mm Particles at 6 m/s

DIAMETER: 12.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
6.17	854	113	0.14	0.15	1.0935	0.9445	1.2417	0.1212	1.1204	0.8	1.68
6.17	854	113	0.14	0.15		0.9445	1.2417	0.1212	1.1204	0.8	1.68
6.17	854	113	0.05	0.04		1.0121	0.6783	0.1369	0.5414	1.5	2.27
						1.0101	0.6949	0.1368	0.5581	1.5	2.34

TABLE 1.3 Burning Data of Suncor Coke for 10 mm Particles at 6 m/s

DIAMETER: 10.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Attrition (kg/s x 10 ⁻⁷)	Burn Rate (kg/s x 10 ⁻⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁻⁷)
			Main bed	Return leg	Initial	Final				
6.15	858	113	0.14	0.15	0.616	0.5255	0.0819	0.6722	0.6	1.008
6.15	857	113	0.14	0.15	0.616	0.5255	0.0819	0.6722	0.6	1.008
6.17	854	113	0.14	0.15	0.6940	0.6127	0.0901	0.5874	0.5	0.881

TABLE 1.4 Burning Data of suncor Coke for 8 mm Particles at 6 m/s

DIAMETER: 8.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Return leg		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed				Initial	Final					
6.17	854	113	0.14		0.15		0.335	0.2861	0.4075	0.0548	0.3526	0.4	0.529
6.14	857	113	0.14		0.15		0.315	0.2645	0.4208	0.052	0.3687	0.4	0.553
6.17	857	113	0.14		0.15		0.315	0.2755	0.3292	0.0527	0.2764	0.3	0.414

TABLE 1.5 Burning Data of Suncor Coke for 6 mm Particles at 6 m/s

DIAMETER: 6.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	(atm)	Return leg	Initial	Final				
6.17	854	113	0.14		0.15	0.145	0.1074	0.3133	0.2832	0.4	0.424
6.17	854	113	0.05		0.04	0.145	0.131	0.1166	0.081	0.4	0.341
6.14	857	113	0.14		0.15	0.133	0.1115	0.1792	0.1498	0.2	0.225
6.14	857	113	0.14		0.15	0.133	0.1125	0.1708	0.1414	0.2	0.212
6.14	857	113	0.14		0.15	0.133	0.1165	0.1375	0.1078	0.1	0.162

TABLE 1.6 Burning Data of Suncor Coke for 4 mm Particles at 6 m/s

DIAMETER: 4.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
6.07	844	112	0.0725	0.0725	0.0395	0.031	0.0708	0.0126	0.0582	0.2	0.168
6.15	858	112	0.14	0.15		0.0265	0.1083	0.0122	0.096	0.2	0.144
						0.0275	0.1	0.0124	0.0876	0.2	0.131
						0.0255	0.1167	0.0121	0.1045	0.2	0.157
						0.0264	0.1092	0.0122	0.0969	0.2	0.145
						0.027	0.1042	0.0123	0.0918	0.2	0.138

TABLE 2.1 Burning Data of Suncor Coke for 14 mm Particles at 7 m/s

DIAMETER: 14.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
7.13	854	113	0.065	0.05	1.685	1.463	1.85	0.1862	1.6637	2.9	5.375
7.13	854	113	0.065	0.05	1.685	1.296	3.2417	0.1796	3.062	7.3	9.89*

*Chipping suspected

TABLE 2.2 Burning Data of Suncor Coke for 12 mm Particles at 7 m/s

DIAMETER: 12.0 mm

TEST DURATION: 1200 sec

RED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² -s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
7.07	854	113	0.115	0.10	1.0935	.9530	1.1708	0.1486	1.022	0.9	1.866
7.07	854	113	0.115	0.05	"	.9579	1.13	0.1646	0.965	1.0	1.762
7.13	854	113	0.065	0.05	1.0640	.9370	1.0583	0.1376	0.9206	1.7	2.974
					"	.9165	1.2291	0.1367	1.0924	2.2	3.529
					"	.9115	1.2708	0.1364	1.1343	2.3	3.665
					"	.8900	1.45	0.1349	1.3151	1.4	2.605
7.07	849	113	0.106	0.116	"	.8760	1.5667	0.1342	1.4324	1.6	2.838
					"	.8505	1.7792	0.133	1.6461	1.9	3.261

TABLE 2.3 Burning Data of Suncor Coke for 10 mm Particles at 7 m/s

DIAMETER: 10.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
7.13	854	113	0.065	0.05	0.6160	0.5220	0.7833	0.0944	0.6888	1.6	2.225
7.13	854	113	0.065	0.05	"	0.5355	0.6708	0.0952	0.5756	1.3	1.859
7.07	849	113	0.106	0.116	"	0.4870	1.075	0.0921	0.9828	1.3	1.947
					"	0.4845	1.0958	0.0919	1.0038	1.3	1.988
					"	0.3720	2.0333	0.0856	1.9477	3.2	3.858*

54

*Chipping suspected

TABLE 2.4 Burning Data of Suncor Coke for 8 mm Particles at 7 m/s

DIAMETER: 8.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
7.13	854	113	0.065	.05	0.315	0.2465	0.5708	0.0589	0.5118	1.6	1.653
					"	0.2582	0.4733 ¹	0.0598	0.4133	1.2	1.335
					"	0.2557	0.4942	0.0596	0.4345	1.3	1.403
					"	0.2354	0.6633	0.0579	0.6054	1.0	1.199
7.07	849	113	0.106	.116	"	0.2320	0.6917	0.0577	0.6339	1.1	1.256
					"	0.2305	0.7042	0.0576	0.6466	1.1	1.28
					"	0.2218	0.7767	0.0569	0.7197	1.2	1.426
					"	0.1875	1.0625	0.0545	1.0079	1.9	1.997

TABLE 2.5 Burning Data of Suncor Coke for 6 mm Particles at 7 m/s

DIAMETER: 6.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
7.13	854	113	0.065	0.05	0.133	0.0955	0.3125	0.0324	0.2799	1.1	0.905
					"	0.1005	0.2708	0.0328	0.2379	0.9	0.768
					"	0.0940	0.325	0.0322	0.2927	1.2	0.945
					"	0.0965	0.3041	0.0324	0.2717	1.1	0.877
7.07	849	113	0.106	0.116	"	0.0898	0.36	0.0317	0.3283	0.7	0.65
					"	0.0885	0.3708	0.0316	0.3393	0.8	0.672

TABLE 2.6 Burning Data of Suncor Coke for 4 mm Particles at 7 m/s

DIAMETER: 4.0 mm

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

Velocity (m/s)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
7.13	854	113	0.065	0.05	0.0395	0.0227	0.14	0.0136	0.1264	0.8	0.408
					"	0.0214	0.1508	0.0134	0.1374	0.9	0.444
					"	0.0205	0.1583	0.0133	0.145	1.0	0.468
					"	0.0220	0.1458	0.0135	0.1323	0.9	0.427
7.07	849	113	0.106	0.116	"	0.0215	0.15	0.0134	0.1365	0.9	0.441
					"	0.0185	0.175	0.0129	0.162	0.6	0.321

TEST 3.1 Burning Rate of Syncrude Coke at 7 m/s

VELOCITY: 7.2 m/s

TEST DURATION: 1200 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

SYNCRUDE COKE

Initial Diameter (mm)	Temperature (°C)	Solid Recycle (kg/m ² -s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
13.1	863	112	0.1	0.11	1.3420	1.0708	2.26	0.1558	2.1041	2.3	4.419
11.8					0.9715	0.8120	1.3292	0.1274	1.2018	1.4	2.524
5.9					0.1220	0.0926	0.245	0.031	0.2139	0.5	0.449
5.9					0.1220	0.0820	0.3333	0.0299	0.3033	0.7	0.637
5.9					0.1220	0.0875	0.2875	0.0305	0.2569	0.6	0.539
6.1					0.1330	0.1051	0.2325	0.0332	0.1992	0.4	0.418
6.1					0.1330	0.1103	0.1892	0.0337	0.1554	0.3	0.326

TEST 3.2 Burning Rate of Ssuncor Coke in Turbulent Fluidized Bed Regime

VELOCITY: 4.1 m/s (Turbulent Regime)

TEST DURATION: 1022 sec

BED MATERIAL: sand 135 micron, 2600 kg/m³

VOIDAGE: .87 Bottom

.99 Top. High fluctuation of bed pressure drop noted

Initial Diameter (mm)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh*	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
13.8	818	113	0.05	0.05	1.6045	1.3209	2.7749	0.1017	2.6728		11.226
12.1					1.0835	0.8464	2.3199	0.0771	2.2428		9.419
12.1					1.0835	0.8511	2.2739	0.0772	2.1967		9.226
10.4					0.6940	0.5210	1.6927	0.0566	1.6359		6.871
10.4					0.6940	0.5121	1.7798	0.0563	1.7233		7.238
8.2					0.3350	0.2249	1.0773	0.0337	1.0434		4.382
8.2					0.3350	0.2245	1.0812	0.0337	1.0474		4.399
6.2					0.1450	0.0736	0.6986	0.018	0.6805		2.858
6.2					0.1450	0.0790	0.6458	0.0184	0.6274		2.635
4.7					0.0650	0.0199	0.4413	0.0096	0.4316		1.813

*Sherwood numbers calculated were mostly negative. Underestimation of attrition in the turbulent regime may be the reason.

TEST 3.3 Burning Rate of Suncor Coke at 6.8 m/s

VELOCITY: 6.8 m/s

TEST DURATION: 300 sec for 10.1 mm and 1200 sec for 7.2 & 5.3 mm

RED MATERIAL: sand 135 micron, 2600 kg/m³

Initial Diameter (mm)	Temperature (°C)	Solid Recycle (kg/m ² s)	Oxygen Partial Pr (atm)		Weight (gm)		Weight Loss (kg/s x 10 ⁷)	Attrition (kg/s x 10 ⁷)	Burn Rate (kg/s x 10 ⁷)	Overall Sh	Burn Rate Referred to 21% O ₂ (kg/s x 10 ⁷)
			Main bed	Return leg	Initial	Final					
10.1	854	103	0.115	0.115	0.6310	0.5936	1.2467	0.0947	1.1519	1.3	2.103
10.1					0.6300	0.5876	1.4133	0.0944	1.3189	1.6	2.408
10.1					0.6300	0.5853	1.49	0.0943	1.3957	1.7	2.549
10.1			0.127	0.127	0.6298	0.5126	3.9067	0.0905	3.8162	6.3	6.969
7.2					0.3200	0.1705	1.2458	0.0569	1.1889	2.2	1.966
5.3					0.1265	0.1037	0.19	0.0344	0.1556	0.3	0.257

8. REFERENCES

- Arena, U., M. D'Amore and L. Massimilla, "Carbon Attrition During the Fluidized Combustion of A Coal", *AIChE J.*, 29, p. 40 (1983).
- Basu, P., "Burning Rate of Carbon In Fluidized Beds", *Fuel (U.K.)*, 56, p. 390, Oct. 19 (1977).
- Basu, P. and D. Subbarao, "Mass Transfer, Attrition and Burning Rate in Turbulent Beds", in preparation, June 1985.
- CANMET Report No. ERP/ERL 82-27 (TR), "Fluidized Bed Combustion of Suncor Coke", Aug. (1981).
- Davidson, J.F., Private Communication, ICREC Conf. (1984).
- Daw, C.S. and R.P. Krishnan, "Combustion Kinetics of Western Kentucky No. 9 Coal", Oak Ridge National Laboratory, Report No. ORNL TM-8604, Sept. (1983).
- Essenhigh, R.H., R. Frosberg and J.B. Howard, *Ind. Eng. Chem.*, 47 pp. 33-43 (1965).
- Field, M.A., *Combustion and Flame*, 13, p. 237 (1967).
- Kunii, D., Levenspiel, D., *Fluidization Engineering*, Krieger, N.Y., p. 199, (1977).
- Kwauk, M., Private Communication (1984).
- La Nauze and Jung, Paper 4.2, 8th Int. Conf. on Fluidized Bed Combustion, Houston (1985).
- Laurendeau, N.M., *Prog. Energy Combustion Science*, 4, p. 221 (1978).
- Mulcahy, M.F.R. and Smith, I.W.R. *Rev. Pure and Applied Chemistry*, 19, p. 81 (1969).
- Petersen, E.E., Chemical Reaction Analysis, Ch. 4, Prentice-Hall, N.J. (1965).
- Subba Rao, D. and Basu, P., "Pressure Profile In A CFB", to be communicated, June (1985).
- Resnick, W.E. and R.R. White, *Chem. Eng. Progr.*, 45, p. 377 (1949).
- Ross, I.B., Patel, M.S. and Davidson, J.F., "The Temperature of Burning Carbon Particles in Fluidised Beds", *Trans IChemE*, vol. 59, p. 87, (1981).
- Stromberg, L., "Experiences of Coal Combustion In A Fast Fluidized Bed", *Archivum Combustionis*, Vol. 1-1981, No. 1/2.

Turnbull, E., Kossakowski, E.R. and Davidson, J.F., "The Effect of Pressure on the Combustion of Char In Fluidized Beds", Chemical Engineering Research and Design, v. 62, p. 223 (1984).

Van Swaaij, W.P., Chemical Reaction Engineering Reviews - Houston, ACS Symposium Series No. 72, Washington, D.C., p. 215, (1978).

Wicke, E., Proc. 5th Symposium (Int.) Combustion, p. 245 (1955).

Young, B.C. and I.W. Smith, "The Kinetics of Combustion of Petroleum Coke Particles At 1000 to 1800 K", 18th Symposium on Combustion, pp. 1249-1254, (1981).

APPENDIX I

**ULTIMATE & PROXIMATE ANALYSIS
OF SUNCOR COKE**



ULTIMATE AND PROXIMATE ANALYSIS

Requested by: Dr. D. S. S.

Date Supplied: Oct 5/84 1984

Analyst: _____

Date Completed: Dec 14/84 1984

Client's No.: _____

TUNS No.: Suncore PB002
PB003

Remarks: Suncore coal

PROXIMATE ANALYSIS

		Average Analysis		
		I	II	AR*** DB** MMFD*
Moisture	,%			< 0.10 - -
Ash	,%			3.05 3.05 -
Volatile Matter	,%			10.42 10.42 -
Fixed Carbon	,%			- - -
Fuel ratio				- - -
Gross Calorific Value				- - -

Dec 14
Coal Lab.

ULTIMATE ANALYSIS

		Average Analysis		
		I	II	AR*** DB** MMFT*
Carbon	,%			84.45 - -
Hydrogen	,%			3.62 - -
Nitrogen	,%			1.57 - -
Oxygen	,%			3.05 - -
Sulphur	,%			7.31 - -
Total	,%			- - -
Pyritic	,%			- - -
Sulphate	,%			- - -
Organic	,%			- - -

*MMFD = Mineral matter free basis

** DB = Dry Basis

***AR = As received

Serial No.

APPENDIX II

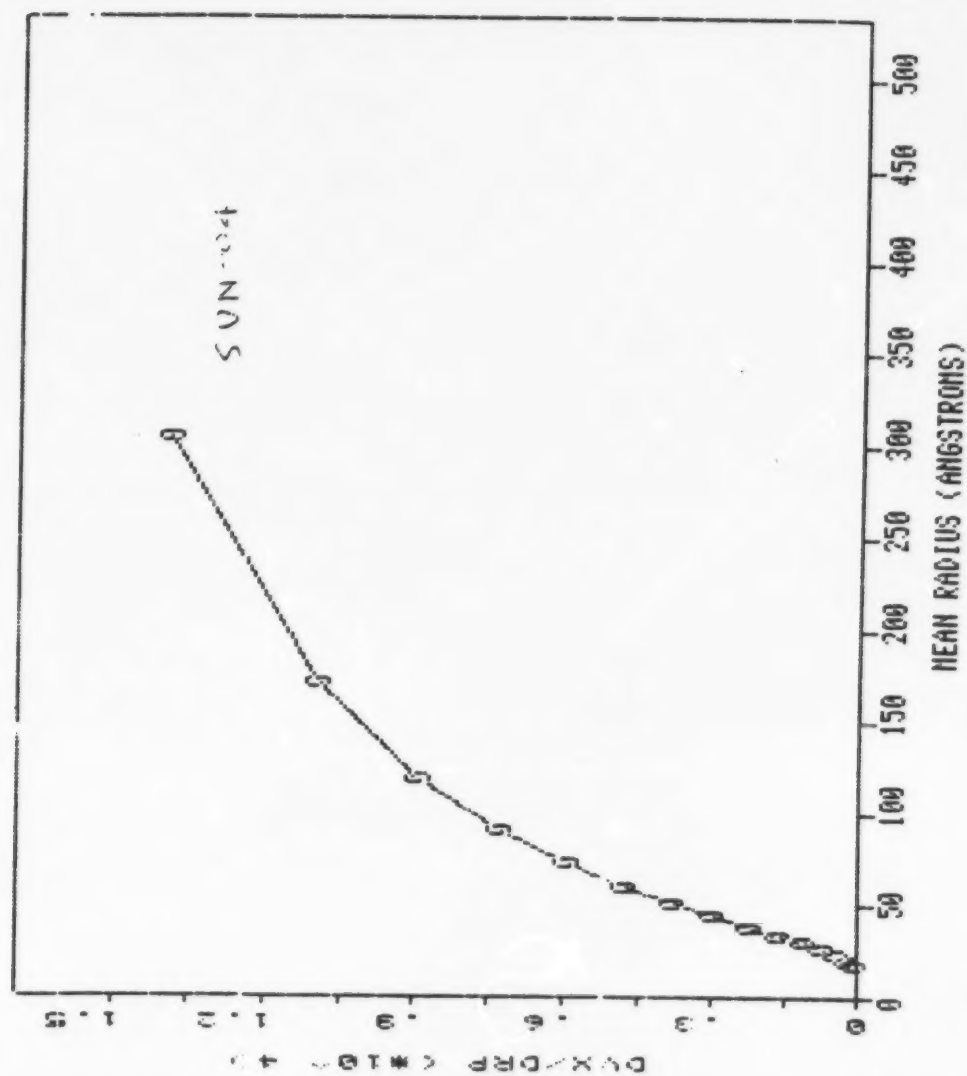
DISTRIBUTION OF SUNCOR COKE PORE AREA

SUN04

FRESH COKE

BET SURFACE AREA -----

THE AMOUNT OF COAL USED IN THE TEST GIVEN IN GRAMS	1
THE ADSORBATE USED IN THE TEST	N-HEXANE
THE CONCENTRATION OF ADSORBATE USED IN THE TEST IN MMOL./CM ³	.00196
THE COEFFICIENT OF CORRELATION FOR THE FIT OF THE LINE	.982999
THE SLOPE OF THE LINE	52.828
THE INTERCEPT OF THE LINE	21.5397
THE VALUE OF THE CONSTANT C	3.45259
THE VALUE OF THE RELATIVE PRESSURE WHEN THE MONO-LAYER IS FORMED	.349881
THE AMOUNT (MMOL/G) OF ADSORBATE COVER- ING THE SURFACE OF THE MATERIAL	1.34467E-02
THE ESTIMATE OF THE SURFACE AREA GIVEN IN SQUARE METERS/GRAM IS	3.18855 -----



SUN04

 PORE SIZE DISTRIBUTION (CONT.)

DVI ---	DT*SUM S -----	VP ---
1.20937E-04	3.71706E-06	1.42006E-04
1.23973E-04	7.30568E-06	1.56528E-04
1.26792E-04	1.04313E-05	1.68187E-04
1.29354E-04	1.31746E-05	1.78392E-04
1.31982E-04	1.56696E-05	1.88131E-04
1.34766E-04	1.80367E-05	1.97958E-04
1.37709E-04	2.0377E-05	2.08035E-04
1.41058E-04	2.27892E-05	2.19005E-04
1.44974E-04	2.53724E-05	2.31255E-04
1.49494E-04	2.82316E-05	2.45081E-04
1.55015E-04	3.15071E-05	2.61407E-04
1.62166E-04	3.541E-05	2.81691E-04
1.71881E-04	4.0292E-05	3.08196E-04
1.86845E-04	4.68666E-05	3.4687E-04
2.12885E-04	5.67855E-05	4.10904E-04

S -	DVX/DRP -----	SUM S -----
9.31416E-03	6.87016E-07	9.31416E-03
.018345	2.15104E-06	2.76591E-02
2.82892E-02	4.42432E-06	5.59483E-02
3.93293E-02	7.54378E-06	9.52776E-02
.051699	1.13687E-05	.146977
6.56589E-02	1.65657E-05	.212636
8.14974E-02	2.25955E-05	.294133
9.97456E-02	2.97674E-05	.393879
.121085	3.82074E-05	.514964
.146323	4.80203E-05	.661287
.176953	5.94446E-05	.83824
.215436	7.28842E-05	1.05368
.265923	8.89815E-05	1.3196
.337958	1.09524E-04	1.65756
.453816	1.38607E-04	2.11137

THE VOLUME OF MESOPORES : 3.54369E-03 CM^3/G

THE SURFACE AREA OF MESOPORES : 2.11137 M^2/G

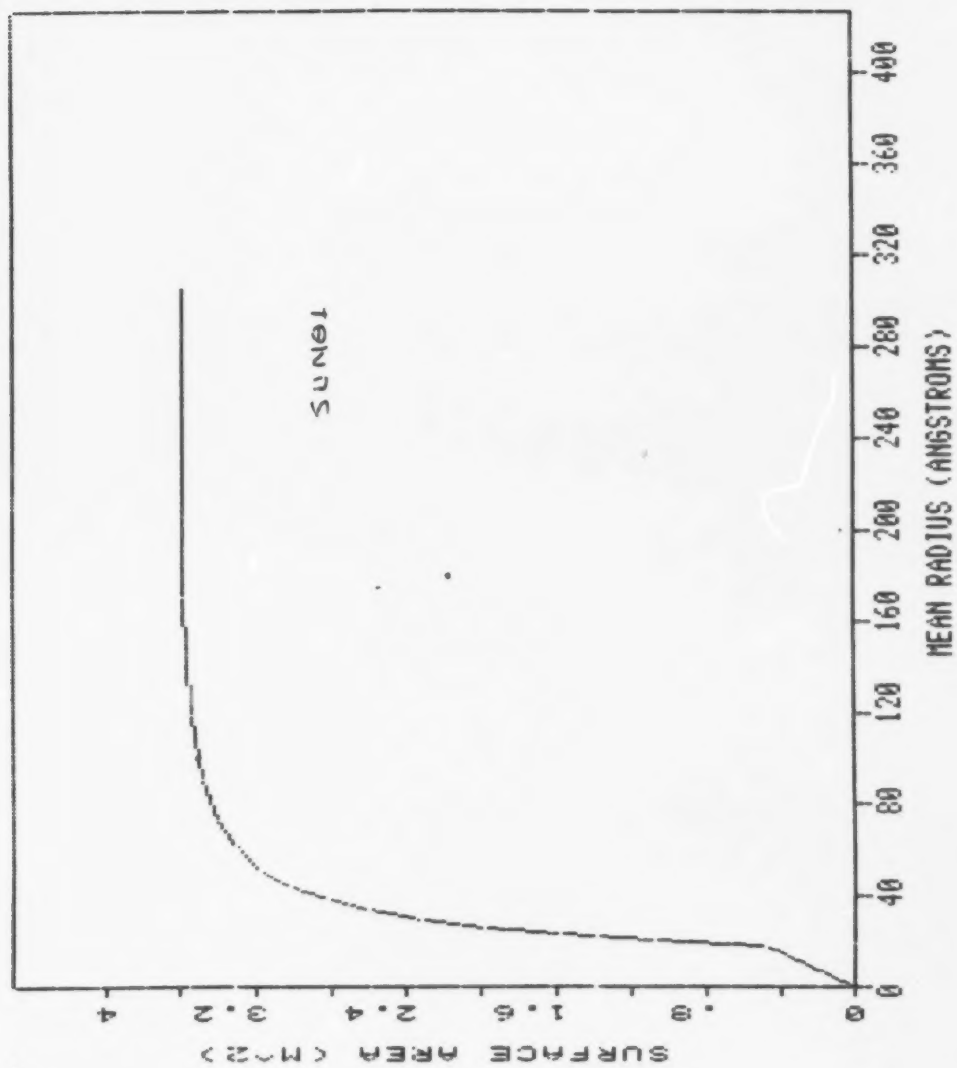
FRESH COKE
BET SURFACE AREA

THE AMOUNT OF COAL USED IN THE TEST GIVEN IN GRAMS	1
THE ADSORBATE USED IN THE TEST	N-HEXANE
THE CONCENTRATION OF ADSORBATE USED IN THE TEST IN MMOL./CM ³	.00196
THE COEFFICIENT OF CORRELATION FOR THE FIT OF THE LINE	.98032
THE SLOPE OF THE LINE	53.5201
THE INTERCEPT OF THE LINE	15.4054
THE VALUE OF THE CONSTANT C	4.47412
THE VALUE OF THE RELATIVE PRESSURE WHEN THE MONO-LAYER IS FORMED	.321006
THE AMOUNT (MMOL/G) OF ADSORBATE COVER- ING THE SURFACE OF THE MATERIAL	1.45084E-02
THE ESTIMATE OF THE SURFACE AREA GIVEN IN SQUARE METERS/GRAM IS	3.44032 -----

SUN01

PREBURNT BEFORE COMBUSTION IN CFB
BET SURFACE AREA

THE AMOUNT OF COAL USED IN THE TEST GIVEN IN GRAMS	3.75
THE ADSORBATE USED IN THE TEST	N-HEXANE
THE CONCENTRATION OF ADSORBATE USED IN THE TEST IN MMOL./CM ³	.00097
THE COEFFICIENT OF CORRELATION FOR THE FIT OF THE LINE	.981809
THE SLOPE OF THE LINE	55.9183
THE INTERCEPT OF THE LINE	10.2167
THE VALUE OF THE CONSTANT C	6.4732
THE VALUE OF THE RELATIVE PRESSURE WHEN THE MONO-LAYER IS FORMED	.262147
THE AMOUNT (MMOL/G) OF ADSORBATE COVER- ING THE SURFACE OF THE MATERIAL	1.51206E-02
THE ESTIMATE OF THE SURFACE AREA GIVEN IN SQUARE METERS/GRAM IS	3.58547
THE NUMBER OF MOLECULES ADSORBED IN THE MONOLAYER	9.10716E+18

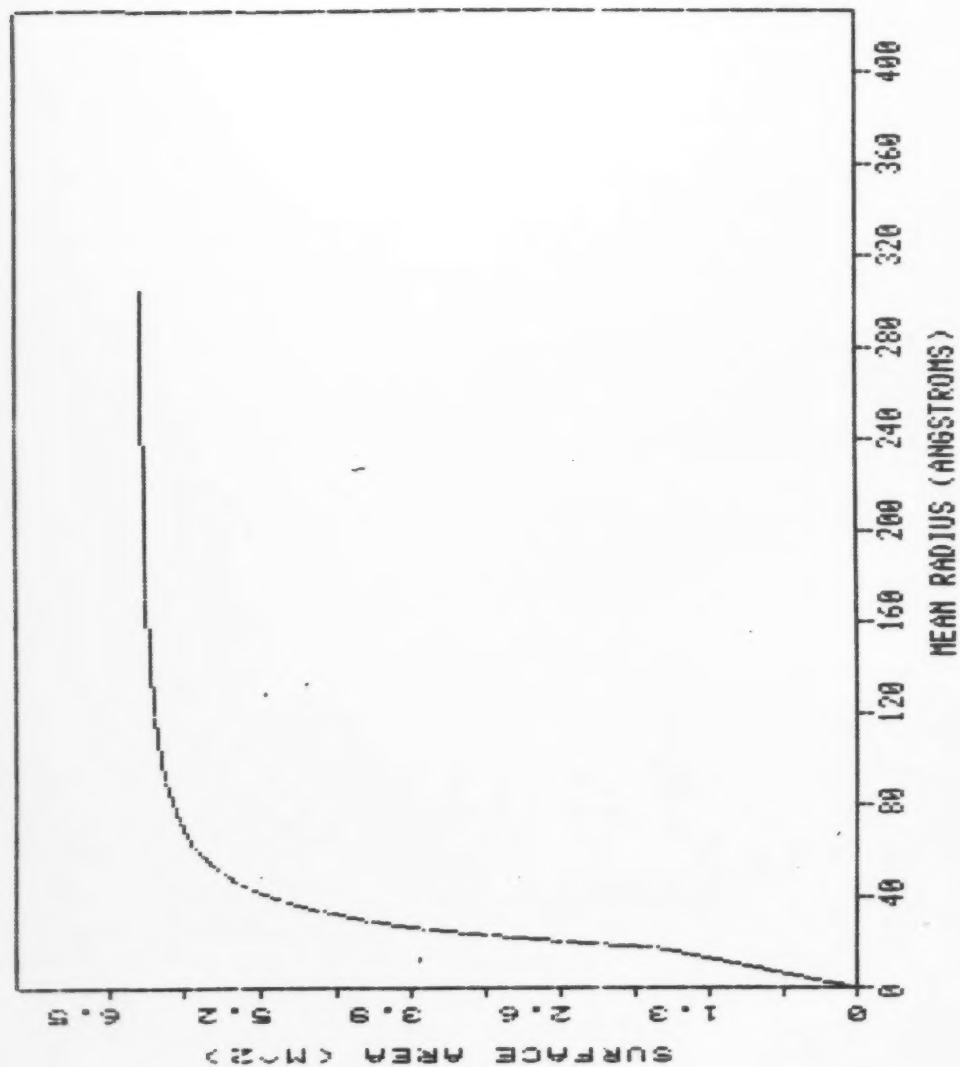


BSS04

AFTER BURNING IN CFB

BET SURFACE AREA

THE AMOUNT OF COAL USED IN THE TEST GIVEN IN GRAMS	.811
THE ADSORBATE USED IN THE TEST	N-HEXANE
THE CONCENTRATION OF ADSORBATE USED IN THE TEST IN MMOL./CM ³	.00097
THE COEFFICIENT OF CORRELATION FOR THE FIT OF THE LINE	.985257
THE SLOPE OF THE LINE	30.5098
THE INTERCEPT OF THE LINE	7.76755
THE VALUE OF THE CONSTANT C	4.92785
THE VALUE OF THE RELATIVE PRESSURE WHEN THE MONO-LAYER IS FORMED	.310571
THE AMOUNT (MMOL/G) OF ADSORBATE COVER- ING THE SURFACE OF THE MATERIAL	2.61251E-02
THE ESTIMATE OF THE SURFACE AREA GIVEN IN SQUARE METERS/GRAM IS	6.19492
THE NUMBER OF MOLECULES ADSORBED IN THE MONOLAYER	1.57352E+19



APPENDIX III

SAND SIZE DISTRIBUTION

III. ANALYSIS OF BED MATERIALS

SAND

DENSITY - 2600 kg/m³

Sieve Size micron	Av. Size micron	Weight (%) X
300 - 500	400	5.22
212 - 300	256	6.71
150 - 212	181	52.61
106 - 150	128	22.58
75 - 106	90.5	5.90
53 - 75	64	4.25
- 53	26.5	2.73

$$D_{\text{mean}} = \frac{1}{10 \times \sum x/d_m} \text{ mm}$$

$$x/d_m = \frac{5.22}{400} + \frac{6.71}{256} + \frac{52.61}{181} + \frac{22.58}{128} + \frac{5.9}{90.5} + \frac{4.25}{64} + \frac{2.73}{26.5} = 0.74095$$

$$D_{\text{mean}} = .135 \text{ mm}$$

APPENDIX IV

ERROR ANALYSIS

ERROR ANALYSIS

Some error is expected in any measurement. The following table shows how these errors are likely to affect the burning rate.

Variables	Error(%)	Reflection On Burning Rate (%)
Velocity	2	1
Temperature	1°C	0.4
Solid Density	5	-2.4
Oxygen Conc.	3	2.8
Residence Time	?	0-50
Weight of Particle	±5	±5

It is seen that the impact of all measured variables except residence time is not very high. However, the residence time in the fast bed can vary widely and this variation can cause an unknown departure of the burning rate from its mean value. Thus, it is necessary to repeat the experiment over a very wide range and to measure the residence time.